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ABSTRACT

TRAYERS, ROBERT, W. JR. Winter Severe Weather: A Case Study of the Intense Squall Line of 6-7 January 1995 in the Carolinas. (Under the direction of Allen J. Riordan.)

A case study was conducted of the evolution of the 6-7 January 1995 intense squall line in the Carolinas. This event was most intense over central and eastern North Carolina and produced wind damage of over 10 million dollars. A record straight-line wind gust of 64 ms^{-1} was recorded at Seymour-Johnson AFB in Goldsboro as the squall line passed the station. Numerous tornadoes also were confirmed. This case is worthy of study because of the rarity of such intense systems in this region in winter. Detailed synoptic and mesoscale surface analyses, upper-air analyses, radar products and satellite images are presented to support this case study.

At 1200 UTC 6 January a strong arctic high pressure system moved off the east coast of the United States setting up an in-situ cold-air damming scenario over western North Carolina. A vigorous low pressure system developed in northern Mississippi with an associated warm front wrapping around the southern Appalachians and into central North Carolina. The front separated the cold 'dammed air' from warm, moist maritime air being transported northwestward from the coast.

Intense warm frontal overrunning was occurring by 0000 UTC 7 January, reducing the static stability above the cold air west of the surface warm front. Intense convection was initiated as a Cold Front Aloft reached

this elevated unstable air. A vigorous low-level jet of 30-35 ms^{-1} just ahead of this squall line was observed in sounding data and confirmed by WSR-88D velocity products. The WSR-88D vertical wind profiles showing winds of 10 ms^{-1} at 1000 feet increasing to nearly 30 ms^{-1} at 2000 feet illustrated the strong low-level shear. West of the front, sounding data and WSR-88D velocity data indicated dry air reaching the squall line transported by a strong southwesterly mid-level jet. As the squall line propagated rapidly toward the coast, extensive wind damage occurred. The strong surface winds were caused by the interaction between the low-level jet east of the squall line and the descending rear inflow jet west of the line producing convectively driven downdrafts. The high momentum air transported downward produced a strong gust front which was responsible for the widespread damage.

WINTER SEVERE WEATHER: A CASE STUDY OF THE

INTENSE SQUALL LINE OF 6-7 JANUARY 1995

IN THE CAROLINAS

by

ROBERT WILLIAM TRAYERS, JR.

A thesis submitted to the Graduate Faculty of
North Carolina State University
in partial fulfillment of the
requirements for the Degree of
Master of Science

MARINE, EARTH AND ATMOSPHERIC SCIENCE

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1996

APPROVED BY:

Dr. G.F. Watson

Dr. S.E. Koch

Dr. A.J. Riordan
Chair of Advisory Committee

Dedication

I dedicate this thesis to my family. To my parents, Robert and Cynthia Trayers, I couln't have done any of this without you! It's been all your love and support throughout the years that's made it possible. To my wonderful wife and best friend, Sandra, you deserve a medal for your heroic patience and support during this trying time in our lives. Your positive attitude and constant encouragement has made it possible for me to finish. Je bent het aller belangrijkste in mijn leven. Ik zal altijd van je houden.

Biography

Captain Robert W. Trayers, Jr. is currently an Air Force Weather Officer assigned to Air Weather Service.

He [redacted] and lived in Lynnfield, Massachusetts throughout his childhood. Captain Trayers attended Lyndon State College where he received his Bachelor of Science Degree in Meteorology. After graduation, he was commissioned as an Air Force Second Lieutenant in May 1990. His first assignment was as a Team Chief at the European Forecast Unit in Traben-Trarbach, Germany. His second assignment was to Tyndall AFB, Florida as a Wing Weather Officer. In August 1994 Captain Trayers was selected by the Air Force Institute of Technology to attend North Carolina State University to obtain an advanced degree in Meteorology.

Upon completion of his Masters Degree, Captain Trayers will be assigned to the Air Force Global Weather Central at Offutt AFB, Nebraska.

Robert W. Trayers, Jr. is married to the former Sandra L. Simpson of Victorville, California.

Acknowledgments

The author would like to thank the United States Air Force and the Air Force Institute of Technology for providing the opportunity to obtain an advanced academic degree and for funding this research.

I would like to express my appreciation to my advisory committee, Dr. Allen J. Riordan (Chairman), Dr. Steven E. Koch, and Dr. Gerald F. Watson. Their guidance, inspiration, and tolerance were instrumental in the successful completion of this research.

I would also like to thank Kermit Keeter and Steve Harned of the National Weather Service for their thoughtful discussions and aid in obtaining data for this study.

Many people over the past two years have contributed to the successful completion of this Master's Degree program. I would like to thank a few of them here. For their encouragement and technical expertise, I would like to thank Mile Adams, Bill Bauman, and Bob Rozumalski. For everyday support and friendship, I thank Deb Hoium, Kim Kreis, Ted Melton, Jim O'Conner, Paul Roelle, and Brian Waranauskas.

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1. Introduction

On 6 January 1995 a squall line developed across central South Carolina. This line of storms moved north and eastward into North Carolina where they underwent rapid intensification and moved quickly eastward toward the coast. This single coherent line of convection produced strong downburst type winds across the eastern half of the state including a record gust of 64 ms^{-1} at Seymour-Johnson AFB in Wayne County near Goldsboro, North Carolina (see Fig. 1.1). Numerous F0 and F1 (weak) tornadoes were also confirmed. This line of storms was directly responsible for 2 deaths, 64 injuries, and tens of millions of dollars in damage (NOAA Storm Data, 1995).

Strong squall lines are a common occurrence in this area in spring, but are quite rare during early winter. An examination of the synoptic pattern alone may not have led to a forecast of this type of severe weather. In fact, during the formative stage of the squall line, western sections of North Carolina were dealing with a significant ice storm.

Once the squall line formed the National Weather Service, using the WSR-88D radar, was able to track the storms and effectively warn the public. A closer look at this case provides the opportunity to evaluate those mesoscale ingredients that are important to this type of squall line formation.

1.1 Literature Review

1.1.1 Squall Lines and Mesoscale Convective Systems

Squall lines are defined as "any non-frontal line or narrow band of active thunderstorms" (*Glossary of Meteorology,* 1959). According to Hane (1986), this definition is a bit restrictive. Instead he suggests that a squall line be considered as both broken and continuous lines of convection whether associated with a front or not.

A Mesoscale Convective System (MCS) is a large group or complex of thunderstorms. Houze (1993) defines an MCS as "a cloud system that occurs in connection with an ensemble of thunderstorms and produces a contiguous precipitation area ~ 100 km or more in horizontal scale in at least one direction."

An important and common type of MCS is referred to as a 'squall line with trailing stratiform precipitation'. This type of MCS is characterized by a sharp convective line with an extensive area of trailing stratiform precipitation (Houze, 1993). The case discussed in this paper is of this type, but will be referred to as simply a 'squall line' for the remainder of the paper.

Squall lines are an important atmospheric feature. They are very common in the midwestern United States and account for much of the needed rainfall in that region. Squall lines frequently, however, are responsible for some of our most severe weather including high damaging winds and tornadoes. Slow moving squall lines have been blamed for severe flash flooding.

One of the major problems meteorologists have is being able to accurately forecast squall line occurrence. Although broad areas of thunderstorms are well-forecast, the prediction of squall line formation cannot be given with much confidence more than a few hours in advance. Cotton and Anthes (1989) blame this on the fact that these systems occur on different space scales ranging from the individual thunderstorm to the extratropical cyclone.

Squall lines can form in many different areas within the large scale environment, but most commonly occur in the warm sector of extratropical cyclones (Fig. 1.2). In order for a squall line to form, the atmosphere must have low static stability, with warm, moist air in the low levels, typically transported into the region by a low-level jet. The presence of a mid-level dry layer also adds to the strength of downdrafts by increasing the potential instability. Another important factor in squall line growth is vertical shear of the horizontal wind (Miller, 1972). However, these features alone often will not initiate severe weather; a trigger mechanism is usually required. This trigger can have many forms including convergence along a cold front or warm front (Hane, 1986), a dryline, an outflow boundary, and also dynamic lifting associated with an upper-level disturbance. For the present case, we will be most interested in the role played by the surface front and upper-level disturbance.

Squall lines which produce damaging winds usually occur in a conditionally unstable atmosphere. Such is the case for the event discussed here. Profiles and cross-sectional analyses will illustrate the potential for downward mixing of higher momentum air from aloft to the surface which produce the damaging straight-line winds. Schematic representation of this process will be given later in the paper.

When a squall line passes a surface observing station, certain characteristic changes occur. Figure 1.3 shows the typical response of field variables to a passing squall line. Note the sharp pressure jump. Wind speeds suddenly increase and shift direction; temperature and moisture decrease. The pressure surge at the leading edge of the squall line was described by Fujita (1955). The author showed the downdraft winds form a hydrostatic "thunderstorm high" followed by a "wake depression" (Fig. 1.4), thus explaining the apparent pressure variability characteristically observed on barographs during squall line events. More recent observations suggest non-hydrostatic dynamics are also important in the formation of surface high pressure areas at the leading edge of gust fronts (Parsons, 1987). All of these features will be seen in the event discussed in this paper.

1.1.2 Cold Fronts Aloft

Lichtblau (1936) was one of the earliest investigators to suggest that Cold Fronts Aloft (CFA) are responsible for a significant amount of winter heavy precipitation events. Lloyd (1942) hypothesized that "upper air cold fronts" have a strong relation to the production of severe weather and tornadoes. Only recently has much new work on CFA's appeared. Hobbs et. al. (1990) define a CFA as a "cold frontal zone whose base is situated above the surface in the lower or middle troposphere".

CFA's frequently contribute to squall line formation well ahead of a surface trough. In fact, Hobbs et al. (1990) point out that in a large percentage of events, the structure that the National Meteorological Center (NMC) has analyzed as a classic cold front with a leading squall line is incorrect. Hobbs et al. (1990) show that the analyzed surface cold front should often be depicted as a surface pressure trough, and the squall line ahead of it should be shown as a CFA. These authors suggest that this frequent mis-analysis is probably due to the over-reliance on the Norwegian frontal model. In most cases shown, the surface trough feature analyzed as a cold front had nothing more than a surface wind shift associated with it. Often there was a more significant arctic front trailing this trough.

The large number of mis-analyzed events led Hobbs et al. (1990) to develop a conceptual model called the Cold Front Aloft Model to help explain the presence of these important features (Fig. 1.5). Four common features were identified to help discern the presence of a CFA. They include the following situations:

1. An observed weather distribution not well explained by classic Norwegian frontal model.
2. Heavy precipitation or squall line and the corresponding 500 mb short wave located well-ahead of surface pressure trough.
3. Satellite images confirm main cloud band located ahead of surface pressure trough.
4. Cross-section analysis indicates region of potential instability (equivalent potential temperature (θ_e) decreasing with height) ahead of the surface pressure trough. High pressure off the east coast advected moist air in the lowest layers inland, below a thin dry layer located between approximately 900 and 1500 m.

Cotton and Anthes (1989) describe two classes of squall lines, the "prefrontal" and "the ordinary" type. Hobbs et al. (1990) suggest making a third class of squall lines as "those associated with CFA's".

Businger et al. (1991) describe a case in which a CFA played an important role in squall line initiation over the Piedmont of North Carolina. They observed that the strongest convection occurred just ahead of the cooler, drier air arriving behind the CFA. Also, a maximum in upward vertical motion was observed just ahead of the CFA aiding in the convective initiation.

1.2 Research Objectives

Several features make this squall line event unique over other documented cases, and thus worthy of further study. First, it occurred during the winter, and therefore at a time that is fairly uncommon in this part of the country. Also, the strongest convection developed at night and was not well forecast.

One can hypothesize that the initial outbreak of convection occurred in the cold air above the surface warm front, and was triggered by the arrival of a CFA. The convection rapidly intensified as the developing squall line intersected the surface location of the advancing warm front. Once the squall line tapped the deep supply of warm, moist air, the thunderstorms became severe. Dry air moved into the mid-levels, further destabilizing the atmosphere and enhancing the convection.

To examine this hypothesis, the objectives of the present research are to use all available data to:

- Document this severe weather event as it affected the state of North Carolina.

- Employ synoptic and mesoscale analysis methods together with WSR-88D radar data to determine the presence and influence of a Cold Front Aloft (CFA) in the formation of the squall line.
- Explain the rapid movement and orientation of the line.
- Develop "forecast guidance" for better predicting this type of event.

2. Data and Methods

Surface and upper air data were available from the National Weather Service (NWS) Automation of Field Offices and Services (AFOS) system. Regular hourly surface observations and 12-hourly upper air data were used. WSR-88D radar data were retrieved from the NWS offices at Raleigh, North Carolina and Columbia, South Carolina. Microbarograph and wind gust charts for all stations in North and South Carolina, as well as infrared satellite images, were obtained from the National Climatic Data Center (NCDC).

Detailed hourly surface analyses were completed by hand for the period 2100 UTC 6 January - 0900 UTC 7 January and compared to surface charts produced by the National Meteorological Center (NMC). Upper air data were used to construct the various cross-sectional analyses shown in this work.

Rawinsonde observations were analyzed using the Skew-T/Hodograph Analysis and Research Program (SHARP) workstation (v 1.50) (Hart and Korotky, 1991). This analysis was useful in modifying soundings and in computing thermodynamic stability indices.

All plotted maps were analyzed using the GEMPAK Meteorological and Analysis Software (5.0) program. This program's ability to objectively analyze various fields was of great use in generating a first-guess field for the final analysis.

3. Case Analysis

3.1 Storm Overview

At 2100 UTC 6 January 1995, a high pressure area centered north of Bermuda was exiting the North Carolina coast, while a surface low-pressure system was developing over northeastern Arkansas (Fig. 3.1.1). A strong warm front associated with this system extended across northern Alabama, Georgia, and into the central Carolinas. The air on the warm side of the front was forced northward by a strong southeasterly return flow behind the exiting high pressure. To the south of the developing low pressure center, NMC analyzed a cold front extending along a wind shift line southward through eastern Louisiana. Temperatures are seen to be similar on both sides of this feature. As discussed earlier, this front should more aptly be analyzed as a surface trough, and will hereafter be referred to as such.

Analysis of the 0000 UTC 07 January upper air maps shows a broad trough extending north-south over the Great Plains. At 200 mb the trough line passes through eastern Texas (Fig 3.1.2). A strong (60 m/s) jet extends from Louisiana northeastward through the Ohio Valley. Along the Gulf coast, the jet appears to split; a weaker (45 m/s) branch extends from southern Louisiana to the Florida coast. This southern branch is likely a reflection of the sub-tropical jet. This divergent jet pattern is evident at 300 mb as well (Fig. 3.1.3). Areas such as this where the Polar and Sub-tropical jets split are particularly favorable for severe storms (Djuric, 1994). This divergent jet pattern appears to be similar to the theory developed by Kaplan et al. (1994) for explaining severe weather development in the southeastern United States.

Figure 3.1.4 shows the 500 mb analysis with a broad area of 40+ m/s winds stretching from the Gulf coast northeastward into Pennsylvania. Geopotential height analysis shows a broad trough through the center of the country. The leading edge of cold advection is depicted in Fig. 3.1.4 by a solid line representing the location of the CFA.

The 850 mb analysis for this time is shown in figure 3.1.5. A more sharply defined trough is evident in the height field with its base over Louisiana and Mississippi. On the east side of the trough, a strong low-level jet of 30+ m/s extends from the Florida panhandle northward through North Carolina. The winds at both recording sites in North Carolina exhibit a significant westward ageostrophic component.

Vertical cross-section analysis was performed using 0000 UTC data in order to confirm the presence of a cold front aloft. The line on figure 3.1.6 indicates the upper air stations contributing to the vertical cross-sections. These stations include Topeka, Kansas (TOP), Paducah, Kentucky (PAH), Nashville, Tennessee (BNA), Greensboro, North Carolina (GSO), and Moorehead City, North Carolina (MHX). Figure 3.1.7 a and b show analyses of potential temperature (θ) and equivalent potential temperature (θ_e)

respectively. Following the work of Hobbs et al., (1990) and Businger et al., (1991), a CFA can be analyzed from 300 mb in the west down to 700 mb east of Nashville. In the potential temperature cross section, the front can be placed along the downward sloping θ surface with cooler, drier air evident behind the front. The equivalent potential temperature cross section supports this analysis. Ahead of the CFA near Greensboro, North Carolina (GSO), an area of θ_e decreasing with height up to approximately 850 mb is present, indicating convectively unstable air. The approach of the CFA into the unstable air will be shown to be a key to the initiation of strong convection. In both cases the shallow surface warm front is apparent from central North Carolina westward over Greensboro.

The presence of the CFA is evident in the backing of winds (indicating cold advection) above 700 mb to the west of the front. Also, the 0000 UTC 7 January 500 mb map (Fig. 3.1.4) shows the leading edge of cold advection (heavy solid line) approximately over central Tennessee corresponding to the location of the CFA on the cross-sections. At 1200 UTC 7 January, the 500 mb analysis shows the leading edge of cold advection off the North Carolina coast (Fig. 3.1.8). Although the exact location of the leading edge of cold advection cannot be determined, its position can be estimated to within ± 50 km. Given the approximate location of the leading edge of cold air at 0000 UTC and 1200 UTC, the speed of its movement can be estimated at 24 ms^{-1}.

Figure 3.1.9 depicts estimated locations of the CFA between 0000 UTC and 1200 UTC based on the calculated speed. Further discussion of the CFA and its role in the squall line development will be provided later in this chapter.

The CFA discussed here is similar to the ones described by Hobbs et al. (1990) and Businger et al. (1991). The cross-sectional analyses are similar, and all depict the CFA as extending vertically from 300 mb down to about 700 mb. In each case, there is a sharp decrease in relative humidity and backing of winds with height behind the CFA. Ahead of the CFA, each case had high relative humidities and a region of convective instability in the low layers as shown in Figure 3.1.7 b.

By approximately 0230 UTC 07 January, convection became organized along the warm frontal boundary through South Carolina. Some of the cells in this line grew to become severe, producing two F1 tornadoes and over $5 million damage (NOAA Storm Data, 1995)(Fig. 3.1.10). It was not until 0343 UTC that there was clear evidence of the squall line beginning to extend into North Carolina.

It is interesting to note that the initial development of the squall line in North Carolina occurs in the cool air above the surface warm front, not along the surface frontal boundary as in South Carolina. This situation will be addressed later in the paper. By 0430 UTC Doppler radar at Raleigh showed the rapidly developing squall line extending from west of Raleigh southward into central South Carolina (Fig. 3.1.11). The southern half of the squall line was the most intense with several small bow echoes in the reflectivity pattern indicating the presence of strong, straight-line winds (Rinehart, 1994). At 0455 UTC, as the squall line reached Fort Bragg, it produced a wind gust of 32 ms^{-1}. Forty-seven minutes later, as the line approached Goldsboro, the storms were at their most intense. As the line passed Seymour-Johnson AFB, the storm's maximum gust of 64 ms^{-1} was recorded. As the squall line continued its eastward track, it caused widespread wind damage and power outages occurred. By 0700 UTC, the line reached the coast and began to break up and weaken.

Figure 3.1.10 shows the path and speed of the squall line evolution through North Carolina and summarizes tornado and wind damage reports. There were 5 confirmed tornadoes in the eastern portion of the state and over $6 million damage due to thunderstorm winds (NOAA Storm Data, 1995).

3.2 Surface Analyses

Detailed surface analysis was performed hourly for the entire duration of this event. This section will discuss the evolution of key features in the analysis.

0000 UTC 07 January 1995

Figure 3.2.1 shows a surface analysis for this time. The surface low pressure area is located over northern Kentucky with its associated surface trough extending southward into eastern Alabama. A strong thermal gradient is apparent along the warm front from central Georgia through northeast North Carolina. The cold pool of air over western North Carolina is reflected hydrostatically as a surface pressure ridge. This "wedge" of high pressure is associated with a phenomena called in-situ cold air damming as described by Keeter et al. (1995). This stagnant cold air is apparent in the meteogram (Fig. 3.2.2) for Greensboro, North Carolina (GSO, see Fig. 3.1.6). Winds were light from the northwest and light rain and freezing rain had been falling for several hours. Meanwhile, to the southeast of Greensboro, the warm front is quite strong with temperature changes across the boundary on the order of 18^{0} C over a distance of 100 km.

The trough analyzed west of the warm front is a curious feature. It is reflected in the pressure and wind field but with only weak confluence. This feature later merges with the surface warm front and becomes the squall line. Fritsch et al. (1992) proposed that cool air outflow boundaries are often formed from anticyclonic mesoscale circulations produced by light rain and clouds over the western Carolinas. This description compares well with the formation of the trough feature analyzed here. The squall line in South

Carolina is associated with the warm frontal boundary which is quasi-stationary across the state.

The 0000 UTC sounding for Greensboro, North Carolina (GSO), located near this trough, shows that the depth of the cold saturated air extends up to 925 mb (Fig. 3.2.3). It is just above this boundary where indications of a low-level jet appear, with velocities rapidly increasing to over 30 ms^{-1}. The observed sounding is relatively stable with none of the stability indices indicating any threat of severe weather. However, if the sounding is modified to include the warm moist surface conditions located only about 60 km to the east, the vertical structure is more unstable (Fig. 3.2.4). The lifted index (LI) decreases to -3, and the Convective Available Potential Energy (CAPE) increases to 718 J/kg. The CAPE is represented in figure 3.2.4 by the area between the dotted line and the temperature trace. This line represents the area of positive buoyancy for a parcel lifted from the surface. In this case CAPE values are modest, but supportive of modest convection. The area of maximum ascent is evident between approximately 900 mb and 700 mb, but just above 700 mb the positive buoyancy quickly weakens which suggests low storm tops. Also, one might anticipate diurnal cooling after 0000 UTC would stabilize the surface airmass, thus reducing the chance for significant convection. This however was not the case in this event.

Satellite imagery for this time shows broad cloudiness over the east coast, with enhanced tops over central Georgia and South Carolina along the warm front and associated with showers and thunderstorms (Fig. 3.2.5). The trailing edge of the clouds in east central Tennessee coincides with the location of the CFA identified earlier on cross section analyses. This description of satellite features agrees with other cases involving CFA's described by Hobbs et al., (1990), Businger et al., (1991), and Locatelli and Hobbs, (1995). A weak band of mid-level clouds is located west of the clearing line associated with the surface pressure trough.

0100 - 0200 UTC 07 January 1995

Through 0100 and 0200 UTC, dramatic pressure falls are observed across eastern Virginia and North Carolina north of the surface warm front. These rapid decreases are on the order of 4 - 5 mb in two hours and act to deepen the surface trough north of the warm front as well as weakening the surface ridge to the west. This area of pressure falls is shown by the dashed line in Fig. 3.2.6, acts in turn to accelerate the warm front toward the northwest. The cause of these dramatic pressure falls is beyond the focus of this paper. Although the pressure in western North Carolina decreased, the extent of the meso-high has expanded southward. The trough remains quasi-stationary between Raleigh and Greensboro.

Satellite imagery shows enhanced cloudiness increasing over central South Carolina associated with the increasing convection along the warm front. At this time the CFA should be crossing the Appalachians based on the speed of the leading edge of cold advection aloft discussed earlier. At this point satellite imagery might supply the only information to support the actual location of the CFA. However, satellite imagery shows the rear edge of the cloud tops over eastern Tennessee to be about 250 mb based on the observed black-body temperature of -55 to -60°C. This means that cirrus clouds are masking the actual location of the leading edge of the CFA (see Fig. 3.1.7a). Therefore satellite images are of limited use in locating the exact position of the CFA.

0300 UTC 07 January 1995

Figure 3.2.7 depicts the surface analysis for this time, which is about 1 1/2 hours before the onset of severe weather. The cold-air damming over western portions of North Carolina has weakened considerably, and its associated high pressure ridge has decreased by about 2 mb. A cutoff area of high pressure associated with the cold air 'outflow' described earlier is now evident. Note the increasing strength of the south-southeasterly winds along the coast has forced the warm front further inland. This is illustrated by noting that the temperature at Raleigh (RDU) has risen by 5^0C and the pressure has decreased by over two millibars in one hour.

Figure 3.2.8 a and b show reflectivity and velocity data, respectively, from the WSR-88D radar at the NWS site in Columbia, South Carolina. The line of convection extends from near Charlotte, North Carolina southwestward to Augusta, Georgia with maximum reflectivity of 57 dBZ. The strength of this line of storms is probably underestimated somewhat due to attenuation of the radar beam through the storms located closest to the radar site (Rinehart, 1994). Comparison of this line of storms to the surface analysis illustrates that this initial phase of the squall line did in fact develop along the southern extent of the warm front (Fig. 3.2.8a). From the velocity display, we can determine that the low-level jet ahead of the squall line is more than 32 ms^{-1} from the southwest at approximately 2 km above the surface, at a distance of 120 km from the radar. Behind the squall line, winds are from the west at approximately 30 ms^{-1} at a range of approximately 200 km (height $\cong$ 4 km). This "inbound" jet is likely a reflection of the approaching CFA. Figure 3.2.8 b also clearly shows the wind shift associated with the squall line from Augusta, Georgia to just west of Columbia, South Carolina.

0400 UTC 07 January 1995

The surface warm front has continued its westward progression, and is now near Raleigh where the temperature has jumped 8^{0}C in one hour (Fig.

3.2.9). The high pressure analyzed immediately behind the squall line is termed a "thunderstorm high" by Fujita (1955) and appears very similar to the schematic model depicted in Figure 1.4. The squall line and the warm front are now coincident south of Fayetteville.

Figure 3.2.10 shows a WSR-88D reflectivity image from the Raleigh, North Carolina radar. At 0400 UTC, the northern extent of the convection in South Carolina can be seen edging into North Carolina between Charlotte (CHLT) and Fayetteville (FAYV). An enhanced area of reflectivity just south of Greensboro (GRSB) (Fig. 3.2.10) indicates the initial signs of convection developing above the cool air (i.e. above the front). Based on earlier interpolation, it is at this point that the Cold Front Aloft is approaching the developing squall line further destabilizing the environment and increasing the lift. At 0400 UTC, pressures continued to fall north of the warm front causing the front to continue its northwestward push into North Carolina (Fig. 3.2.9). The front passed Raleigh, North Carolina at 0400 UTC as evidenced by the meteogram (Fig. 3.2.11). By 0429 UTC, the squall line has begun to form near the front west of Raleigh and extend southward into South Carolina.

Based on the 0400 UTC surface analysis (Fig. 3.2.9) and the 0429 UTC reflectivity image (Fig. 3.1.11) the squall line and CFA merged with the warm front causing rapid intensification of convection. This is similar to what occurred with the CFA described by Businger et al. (1991).

Since 0000 UTC no diurnal cooling has occurred, but dewpoints have increased on the east side of the front by 3 to 4° C. This is probably due at least in part to the proximity of the ocean waters.

The air mass ahead of the front which was already convectively unstable as analyzed by the 0000 UTC θ_e cross-section (Fig. 3.1.7b), was at this point destabilized further. Convection was initiated as the CFA reached the surface warm front and tapped into the warm moist surface conditions south of the front.

Doppler velocity imagery for 0429 UTC shows south-southeast surface winds of 10 ms^{-1} increasing to about 35 ms^{-1} from the south at 2000 feet ahead of the squall line. This suggests low-level transport of warm, moist air into the region. Behind the squall line, winds increase to approximately 25 ms^{-1} from the west-southwest at 10,000 feet announcing the arrival of the mid-level dry air behind the CFA.

0500 UTC 07 January 1995

By this time, the squall line is very intense with maximum reflectivities of 58 dBZ and echo tops of approximately 35,000 feet. The line is a single coherent band stretching along the surface warm front from Raleigh southward to Fayetteville and then southwestward into South Carolina. The CFA can be inferred on the 0458 UTC radar image just north and west of Raleigh merging with the warm frontal boundary (Fig. 3.2.12). The squall line merges with the warm front just south of Fayetteville. The surface analysis confirms the location of the warm front and the squall line merging (Fig. 3.2.13). Due to the effects of the thunderstorms, the actual location of the warm front is obscured.

In order to get a better idea of what was occurring in the mesoscale environment at this time, a time-to-space conversion analysis was performed. This procedure (Fujita, 1963) assumes linear, homogeneous movement of the feature being tracked, in this case, the squall line. The procedure involves plotting observations at a given time, then plotting earlier and later observations for the same stations in the line of movement. The location of the earlier and later plots are consistent with the speed of the feature. Microbarograph traces and wind gust recorders were used to fill in the analysis between observation times. Figure 3.2.14 is a time-space analysis for this squall line examined around the 0450 UTC observation. As the squall line passed stations throughout North Carolina, a tell-tale spike was observed in the barograph traces as described by Fujita (1955). This spike is depicted on the time-space analysis as a thunderstorm high immediately following the squall line and a mesolow developing ahead of the squall line. This type of analysis is helpful in placing features on the larger scale maps.

Shortly after 0500 UTC, the initial damage began to occur all along the squall line. At 0455 UTC, Fort Bragg (near Fayetteville) recorded a wind gust of 32 ms^{-1} and reported numerous trees down and buildings damaged. The strong winds were apparently a result of the thunderstorms mixing the high momentum air from above down to the surface. This high momentum air is evident on the 0504 UTC Doppler velocity image (Fig. 3.2.15) where the winds are southwesterly behind the squall line with velocities of 20 - 25 ms^{-1} at 3 km above the surface. Winds ahead of the squall line were even stronger at 30 - 35 ms^{-1} from the south-southeast.

Johns and Doswell (1992) describe two ingredients that, if present while deep convection is occurring, will initiate and sustain a downdraft. Those two features are precipitation loading and negative buoyancy due to evaporative cooling. Precipitation loading is when the drag of the raindrops acts to enhance the descent of an air parcel. Figure 3.2.16 is an image from the WSR-88D of Vertically Integrated Liquid (VIL). This image illustrates the high volume of precipitation associated with the squall line. The more liquid available the greater the effect of precipitation loading will be on downburst strength.

The second ingredient proposed by the above authors is negative buoyancy due to evaporative cooling. This occurs when precipitation falls through dry middle layers of the atmosphere and evaporates. Figure 3.2.17 a and b are soundings for 0000 UTC 07 January from Moorehead City, North Carolina (MHX) and Charleston, South Carolina (CHS) (both in the warm air). They both have significant dry layers in the mid-levels as described above. Satellite images beginning at 0400 UTC show a narrow dry tongue of air working its way northward from the Florida panhandle (Fig. 3.2.18). This dry air is in the mid-levels and likely extends much further inland than depicted because of the obscuring presence of high clouds above the dry layer. This dry intrusion is to the west of the squall line and is associated with the CFA.

Once the downdraft has developed, it not only has its own downward momentum, but also acts to transport horizontal momentum from aloft down to the surface. In the current case, the vigorous mid-level jet west of the squall line encountered strong convection enabling the high momentum air above to be mixed to the surface in the form of damaging surface winds.

The aliased velocities in Figure 3.2.15 are an indication of turbulence or shear in the area. This is confirmed by checking the Doppler spectrum width (Fig. 3.2.19) which is a measure of the variance of the velocities (Doviak and Zrnic, 1993). This area of turbulence is located where the squall line is most intense.

The strongest evidence of a CFA triggering the squall line is confirmed by the WSR-88D Velocity Azimuth Display (VAD) wind profile taken around the time the squall line passed the Raleigh radar. Figure 3.2.20 indicate winds veering with height implying warm advection in the low layers until 0510 UTC which is the time the squall line passed the radar. After 0510 UTC, the winds above 9,000 feet begin to show backing with height indicating the cold air advection associated with the passage of the CFA (Hobbs et al. 1990). This cold advection can be seen to steadily increase in height through time as the squall line and CFA progress eastward.

At 0531 UTC the squall line was at its strongest, with maximum reflectivities of 61 dBZ. Figure 3.2.21 a and b are enlarged images of reflectivity and velocity for this time. The reflectivity indicates a bow shaped echo beginning to form southwest of Goldsboro (GLD). Doppler velocity shows a very sharp wind shift line along the leading edge of the storms. An area of extremely intense low-level winds of approximately 40 ms^{-1} at a height of 2000 feet is right over Goldsboro (GLD, see Fig. 3.2.21a). These intense winds are folded on the 0531 UTC WSR-88D velocity image (Fig. 3.2.21b). Just west of the squall line, winds are 35 ms^{-1} from the southwest. At 0542 UTC, Seymour-Johnson AFB near Goldsboro recorded surface winds of 38 ms^{-1} gusting to 64 ms^{-1} from the west-southwest. At about this same time two confirmed F1 tornadoes touched down in Wayne and Sampson counties (see Fig. 1.1).

0600 - 0800 UTC 07 January 1995

Radar shows the squall line oriented north - south from Richmond, Virginia to just east of Goldsboro, North Carolina (Fig. 3.2.22). The line then bends back to the southwest and into eastern South Carolina following the warm frontal boundary. Damaging wind reports continued until about 0645 UTC. After this point the squall line began to break up and weaken as it approached the coastal waters. By 0730 UTC, just an isolated band of thunderstorms remained along the coast.

The 0600 UTC surface chart indicates that the large-scale surface pressure trough discussed earlier had merged with the arctic front, which had been trailing it, and crossed the Appalachians (Fig. 3.2.23). The cold front moved rapidly through the area and by 0900 UTC this feature was along the east coast leaving cooler, drier air in its wake.

4. Summary

A study was conducted to document the development and evolution of the intense squall line of 6 - 7 January 1995 over the Carolinas. A strong arctic high pressure area moved off the east coast setting up an in-situ cold air damming scenario over western North Carolina. A developing storm system in the lower Mississippi valley produced a warm frontal boundary which extended into central North Carolina. This warm front marked a strong thermal boundary along which convection rapidly intensified.

Several important features must be present for the formation of convective storms. Djuric (1994) suggests the key atmospheric variables to examine are stability, availability of water vapor, wind shear, environmental lifting and thermal advection. For the case described here, there is potential instability in the low levels, a generous supply of water vapor being transported in southeasterly flow from the coast, and an impressive low-level wind shear profile. The initial lifting mechanism is the warm front described in the previous section, and as already shown, there was abundant warm air advection. The warm advection is important since it enhances the thermal instability of the atmosphere and provides directional wind shear favorable for thunderstorm development (Djuric, 1994). Once strong convection has been initiated, it must be monitored for signs of downburst potential.

Strong damaging winds associated with convection are nearly always caused by outflow at the base of a downdraft (Johns and Doswell, 1992).

These downdraft winds were apparently responsible for the majority of damage which occurred with the case described here. Very strong downdraft winds, similar to those observed in this case, are described by Houze (1993). A schematic diagram of airflow within a 'squall line with trailing stratiform precipitation is given in Figure 4.1. In a case such as this, a strong low-level jet ahead of and directed toward the squall line feeds the upward motion at the leading edge of convection. This flow rises through the convective region and splits near the storm tops. Part of the flow returns to the surface as a downdraft associated with heavy precipitation while the other portion of the split flow rises gently through the trailing stratiform cloud. At the same time there is a downward sloping rear inflow beneath the stratiform cloud. This 'descending rear inflow' enters the cloud just above the radar bright band (melting level) and continues descending into the convective region where it reinforces the existing gust front (Houze, 1993). This process is responsible for strong surface wind gusts and maintaining the surface cold pool necessary to keep the MCS process going.

Houze (1993) states that when the ascending front-to-rear flow is strong, ice crystals from the leading convective line are advected rearward. These crystals grow through vapor deposition which in turn sets up a horizontal buoyancy gradient that enhances the descending rear inflow. The ice crystals descend to the freezing level where they melt and form the radar bright band and then fall to the surface as heavy stratiform rain.

It is apparent that the key ingredient that fuels the process detailed above is the strong low-level jet ahead of the squall line. Figure 4.2 depicts the storm relative flow ahead and behind the squall line. This flow was calculated by vector subtraction and values appear in Figure 4.2.

Low-level shear is important to the development and maintenance of a strong squall line. It has been shown that a squall line with a vertically rising updraft will be stronger than a line with a rearward sloping updraft (Rotuno et al., 1988). For a case similar to this with a strong low-level jet just above the surface, an area of positive horizontal vorticity develops along the inflow region. If the strength of the surface cold pool behind the gust front is strong, enough negative vorticity will be generated along the gust front to balance the positive vorticity. This allows for a truly vertical updraft into the storm (Fig. 4.3). Simple calculations have shown this to be approximately the case for the event discussed here. Calculated values of vorticity are shown in Figure 4.3.

Through examination of 0000 UTC 07 January upper air charts and soundings, it was apparent that due to the establishment of a strong low-level jet right over North Carolina, the environment was somewhat favorable for strong storms to develop due to the strong near-surface shear. However, the stability of the air was not particularly low as evidenced by the soundings (see Fig. 3.2.3). Surface winds east of the front were increasing, thus causing rather vigorous warm frontal overrunning and a feeding inflow to the squall line. Cross-sections were constructed through the area of the warm front. These analyses showed the presence of a significant Cold Front Aloft (CFA) approaching the region from the west.

Satellite and radar imagery as well as 500 mb analyses showed that the CFA progressed rapidly eastward and enhanced the convection occurring in the cool air above the warm front. At approximately 0430 UTC, the CFA is believed to have merged with the warm front causing the squall line to undergo explosive development as the line tapped the warm, moist air ahead of the front. The CFA also brought dry air into the mid-levels. Evidence to support the CFA hypothesis includes data from cross-sectional analysis (see Fig. 3.1.7) and later VAD profiles (see Fig. 3.2.20). Finally, by simple linear interpolation between upper-air analyses, the CFA was located in the general area of convective initiation (Fig. 3.1.9) where it had a north-south linear orientation identical to that of the line of convection.

The squall line continued rapidly eastward and began to break up as it lost strength over the coastal plain. The surface trough and arctic cold front merged over the Appalachians and moved through the state several hours after the squall line ushering in clear, cool conditions over the entire region.

5. Concluding Remarks

5.1 Conclusions

As suggested by Hobbs et al. (1990) many winter time squall line events are mis-forecast because of failure to recognize the presence of a CFA. This is partially because of over-reliance on the traditional Norwegian cyclone model.

Weak convection probably should have been anticipated over central North Carolina at 0000 UTC based on the lifting of air over the warm front. However, with knowledge of the approaching CFA, and the moistening and maintenance of warm temperatures east of the warm front, the forecast might have been modified to call for a more serious threat of severe weather. The potentially unstable environment only needed a weak thunderstorm (downdraft) to entrain the high momentum air aloft to the surface. This process combined with the intense low-level jet was apparently responsible for the damaging winds observed across the area. A conceptual model of the key features of this event is presented in figure 5.1.

During similar synoptic conditions, the following steps may be taken by forecasters to identify signs of a CFA and possible severe weather development:

- Determine the veracity of fronts analyzed on NMC analysis.

- Perform cross-sectional analysis of potential temperature and look for signs of a CFA. These include downward sloping potential temperature surfaces with dry air west of the slope and winds backing with height in this region. If time does not permit an extensive analysis, examine soundings upstream and look for drying aloft and backing of the winds above 700 mb.
- Look for significant low-level jet and strong near-surface shear using WSR-88D velocity products. The jet may provide strong enough inflow into the squall line to produce damaging downburst winds.
- Watch for sudden surface pressure falls ahead of the warm front, causing rapid northward propagation of the frontal surface. This shift may cause threat area to change rapidly.
- Watch the VAD profile at upstream locations for backing of winds with height aloft. This backing is evidence of the passage of the CFA.
- Watch for development of linear reflectivity features on the radar coincident with the expected location of a CFA. As these lines move eastward, they may rapidly intensify as they collide with warm, moist air.
- Use available numerical model forecasts as guidance for movement of CFA.

- Observe satellite imagery carefully. It was not of great use in this case because of obscuring high clouds, but may be helpful in tracking location of a CFA using the trailing edge of associated clouds in infrared imagery.

5.2 Future Research

The research presented in this thesis provides development for a case of an intense winter time squall line triggered by a Cold Front Aloft. Additional research is warranted to better understand the processes at work in this complex event. Future research should include:

- A modeling study of the squall line evolution given these initial conditions.
- Examination of the role of jet stream dynamics.
- Interactions between the rear inflow of the MCS and the mesoscale mid-level jet accompanying the CFA.

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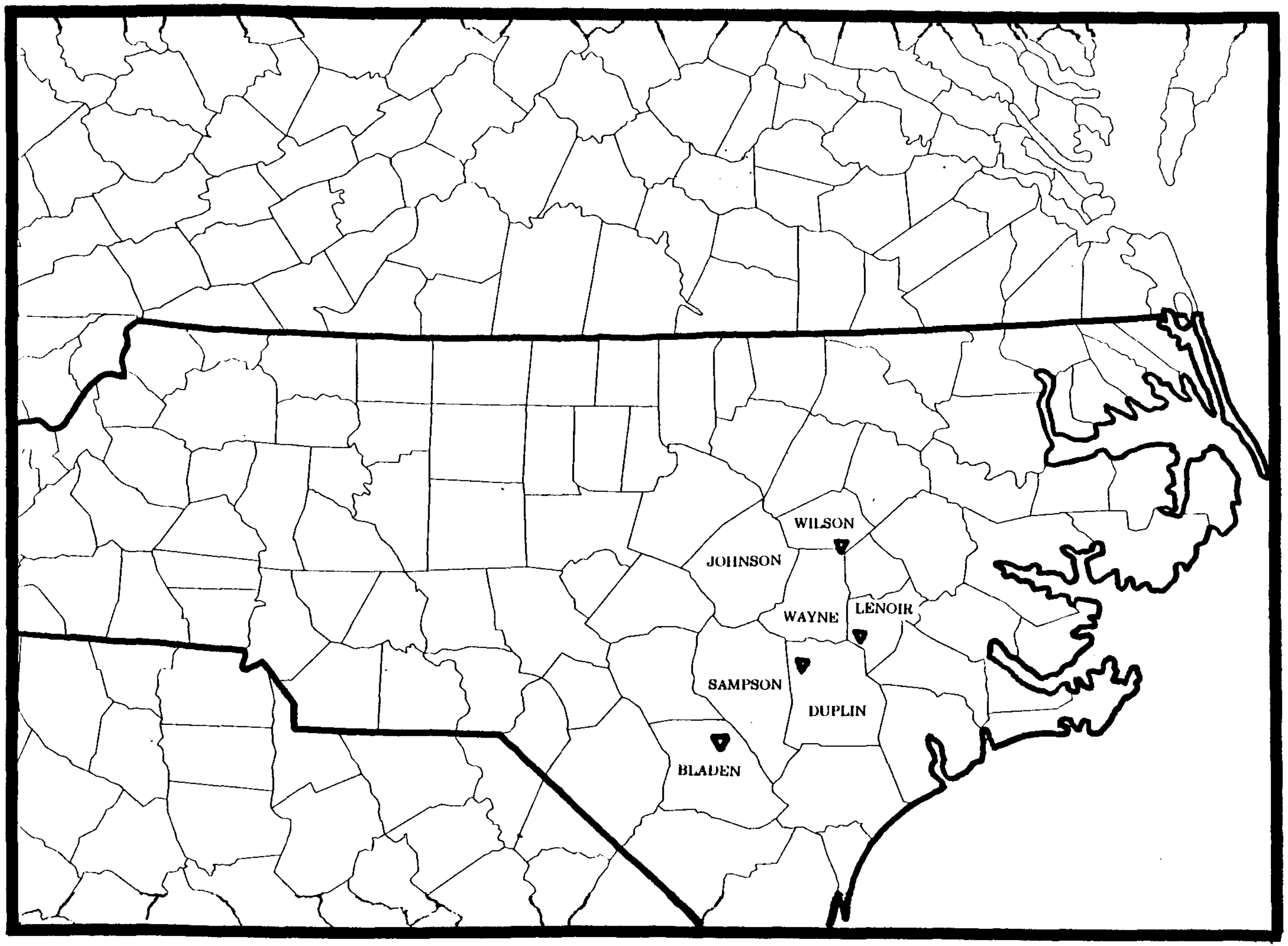


Figure 1.1. North Carolina county map including plots of confirmed tornadoes (∇) from 7 January 1995.

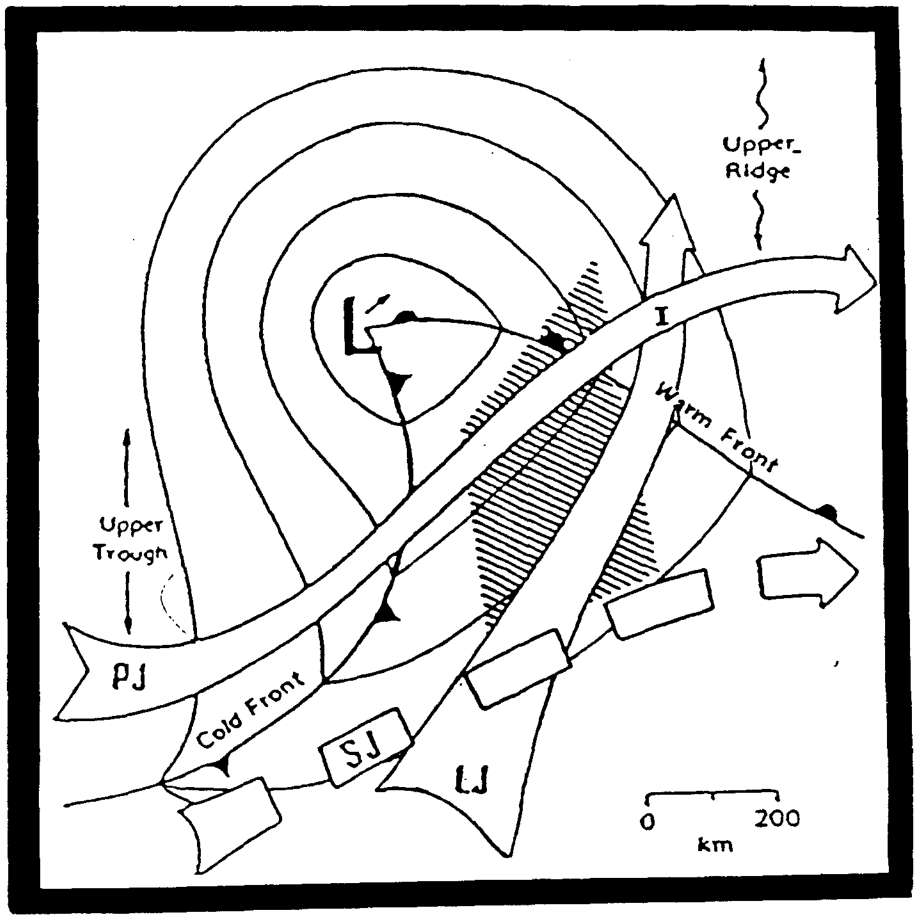


Figure 1.2. Dynamic synoptic pattern favorable for squall line development. PJ is the polar jet, LJ is the low-level jet. Thin lines are sea-level pressure and hatched area represents area favorable for squall line formation. (Johns, 1993)

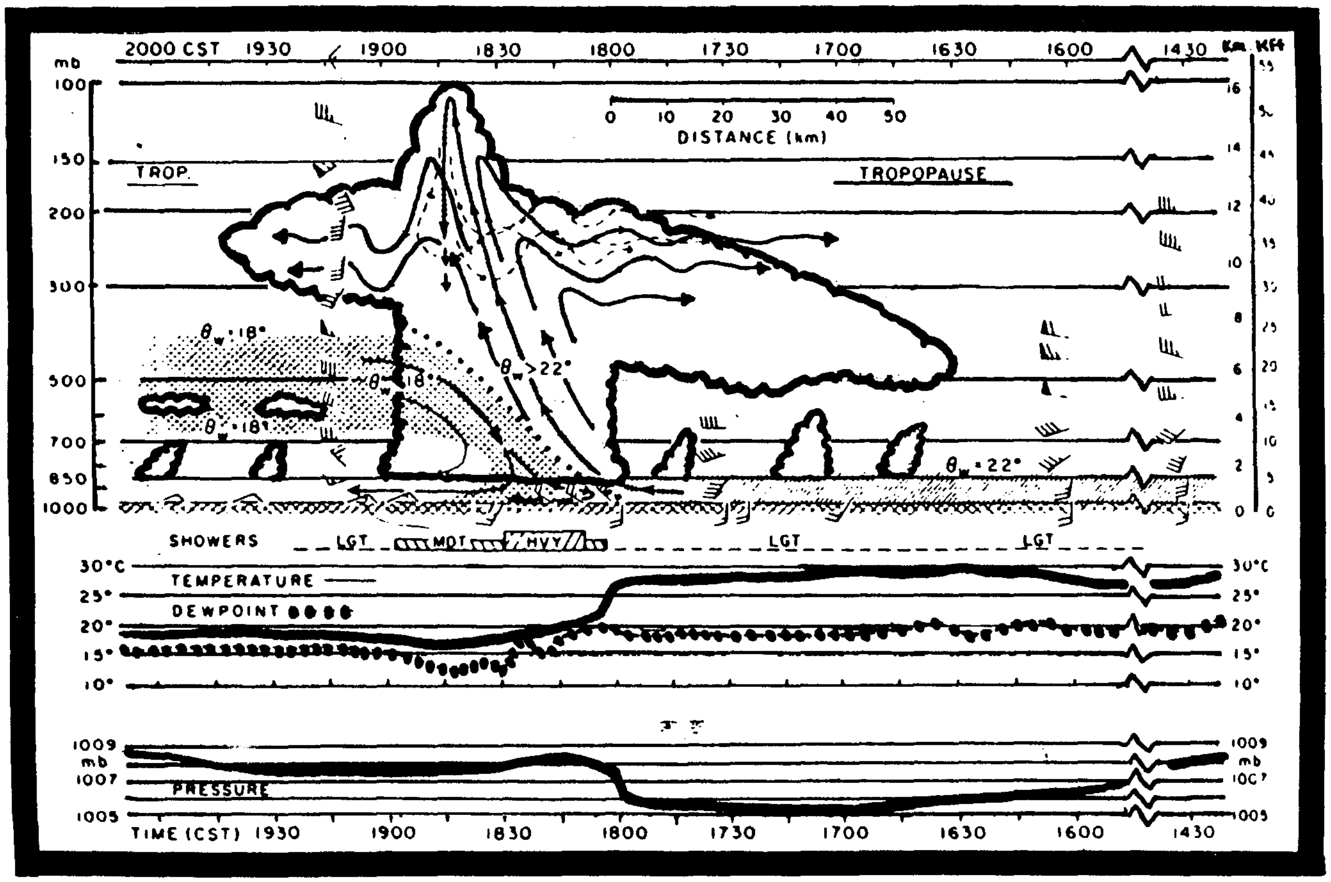


Figure 1.3. Schematic cross section through a squall line, with field variable trends below. Time is from right to left. (Cotton and Anthes, 1989)

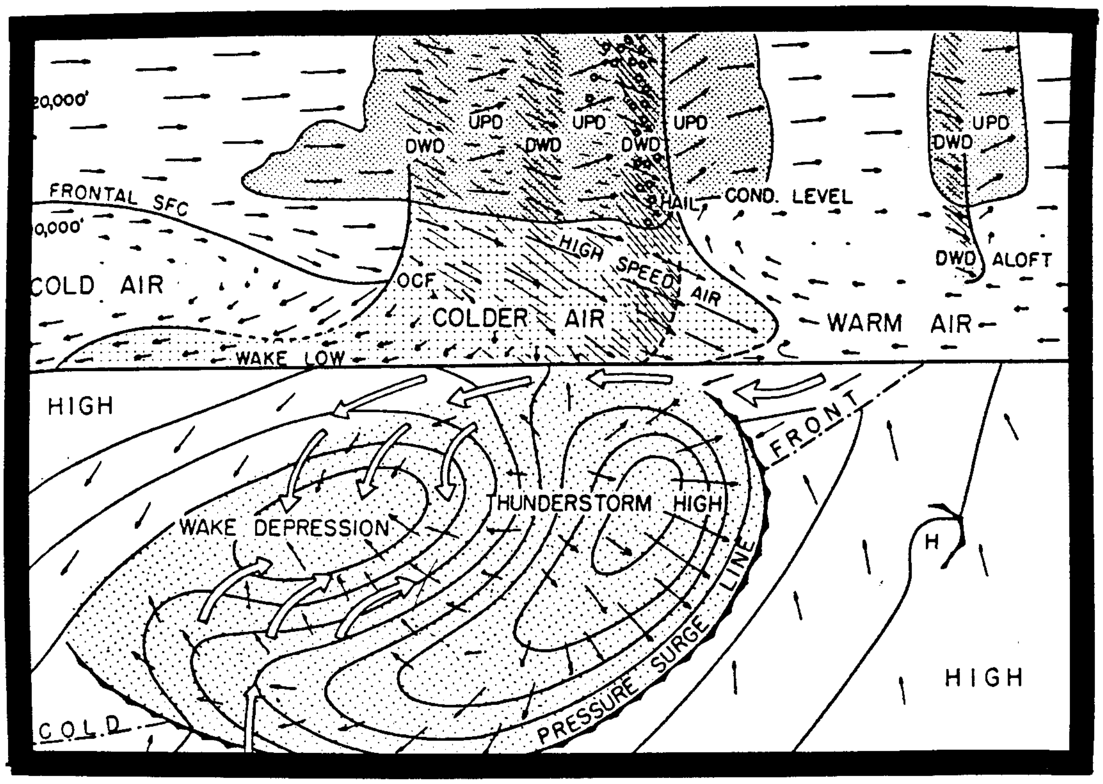


Figure 1.4. Schematic model of a squall line. Top image is a vertical cross section, lower image is in surface plane view. Thin lines are isobars, small arrows are wind vectors. UD is updraft, DD is downdraft. (Fujita, 1955)

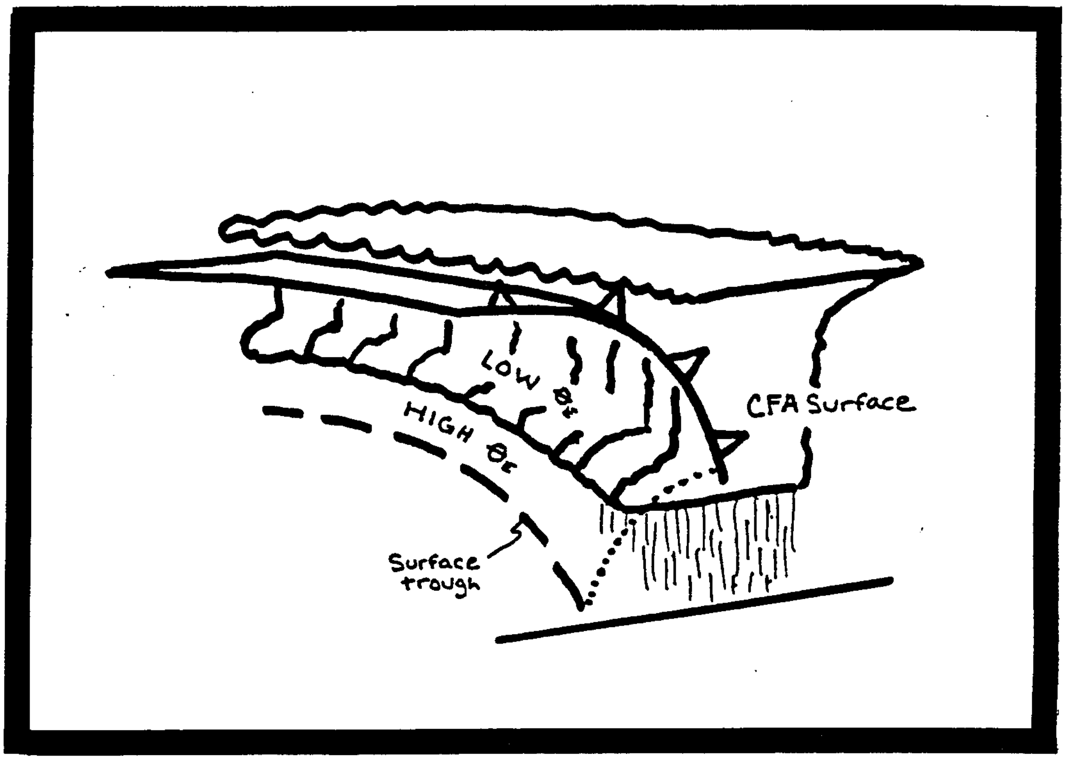


Figure 1.5. Schematic of conceptual Cold Front Aloft Model (Hobbs et al., 1990)

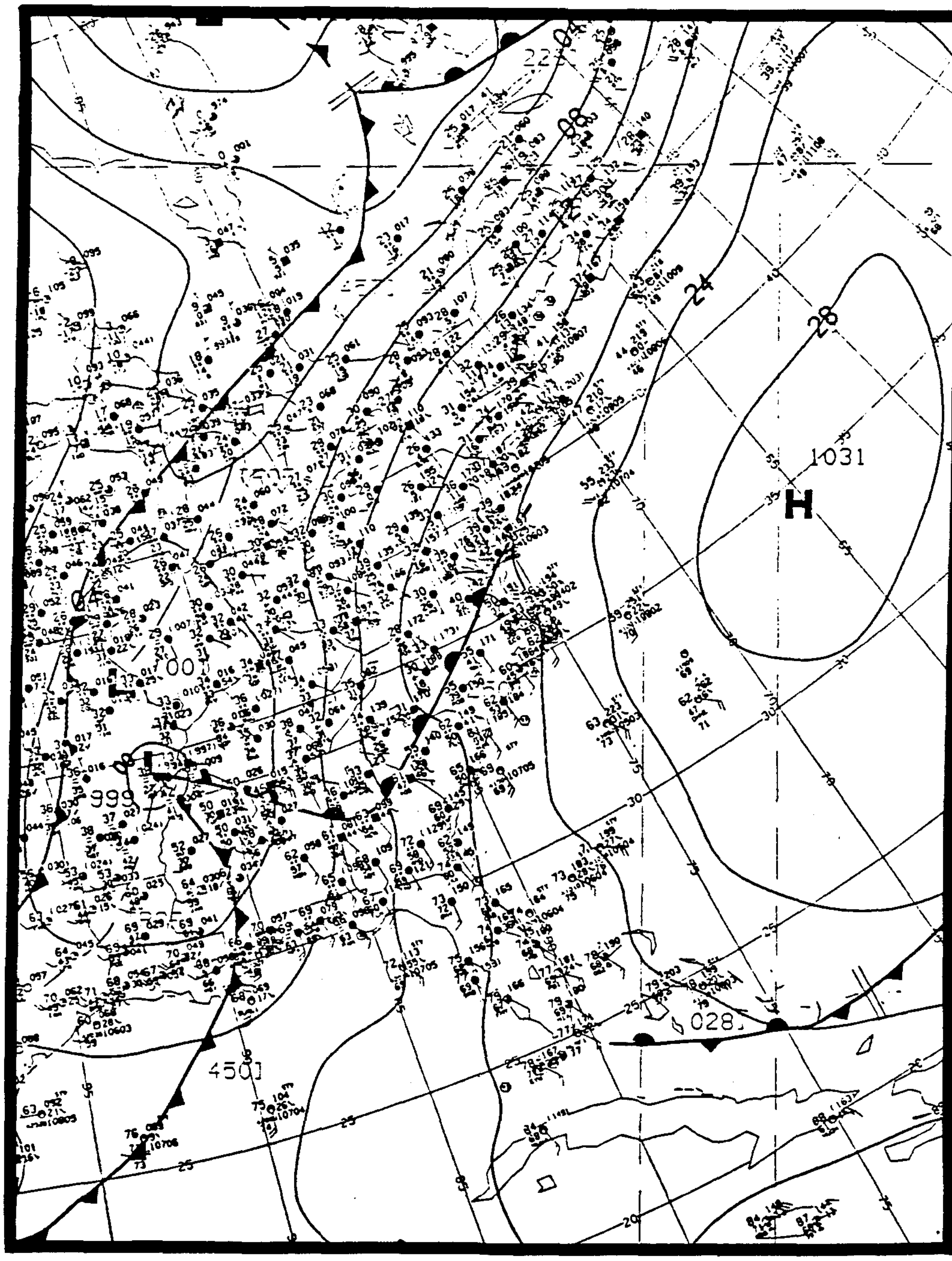


Figure 3.1.1. NMC analysis for 2100 UTC 6 January 1995.

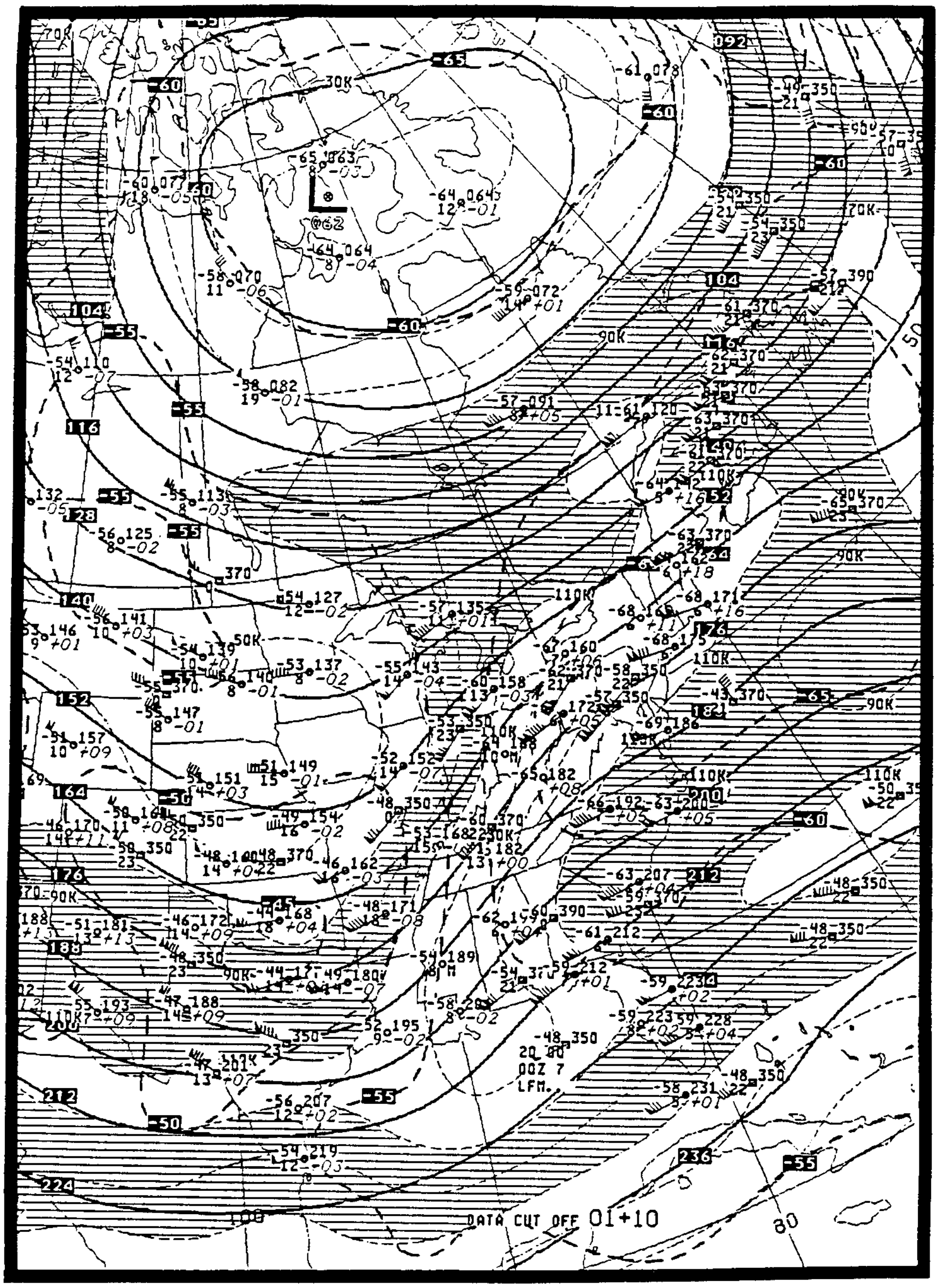


Figure 3.1.2 NMC 200 mb analysis for 0000 UTC 7 January 1995.

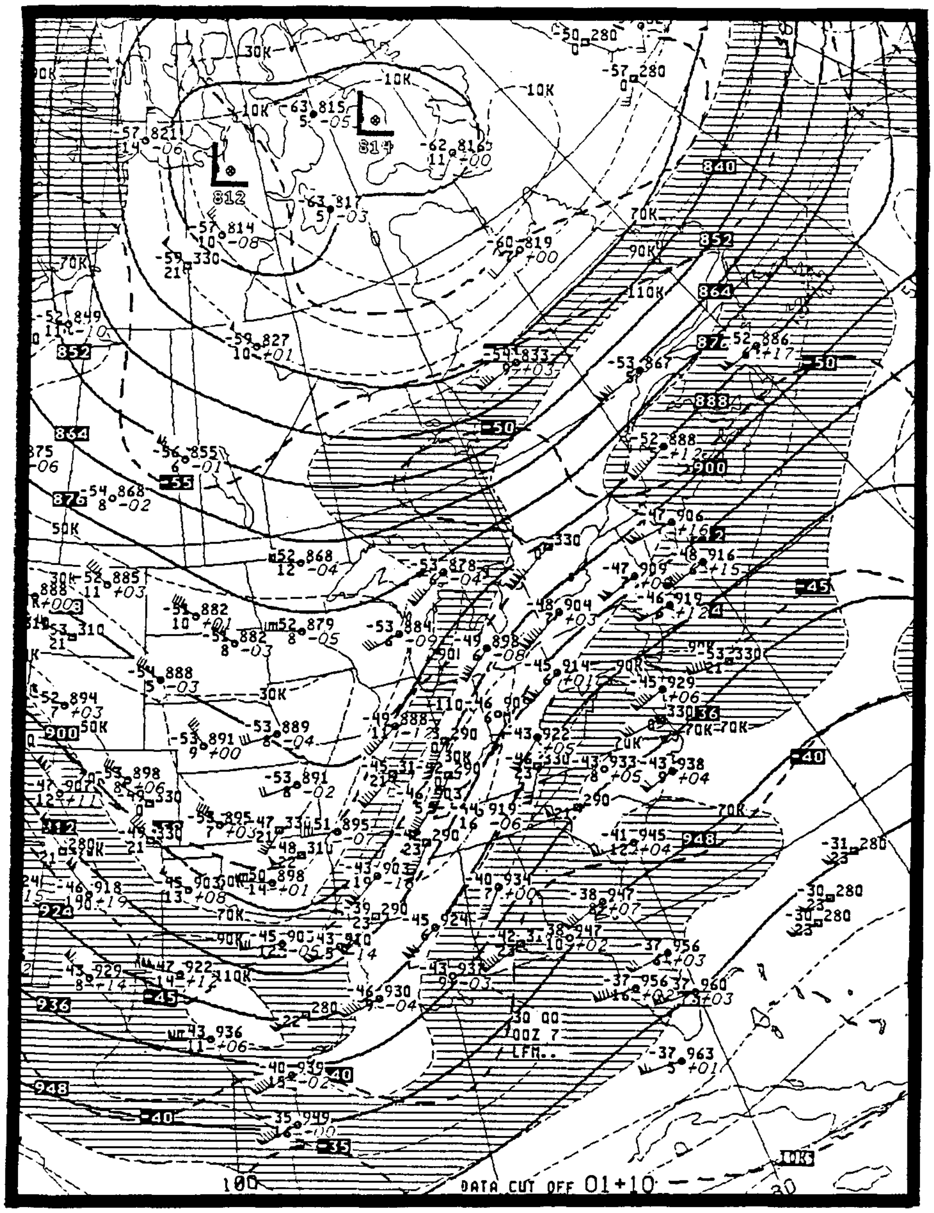


Figure 3.1.3 NMC 300 mb analysis for 0000 UTC 7 January 1995.

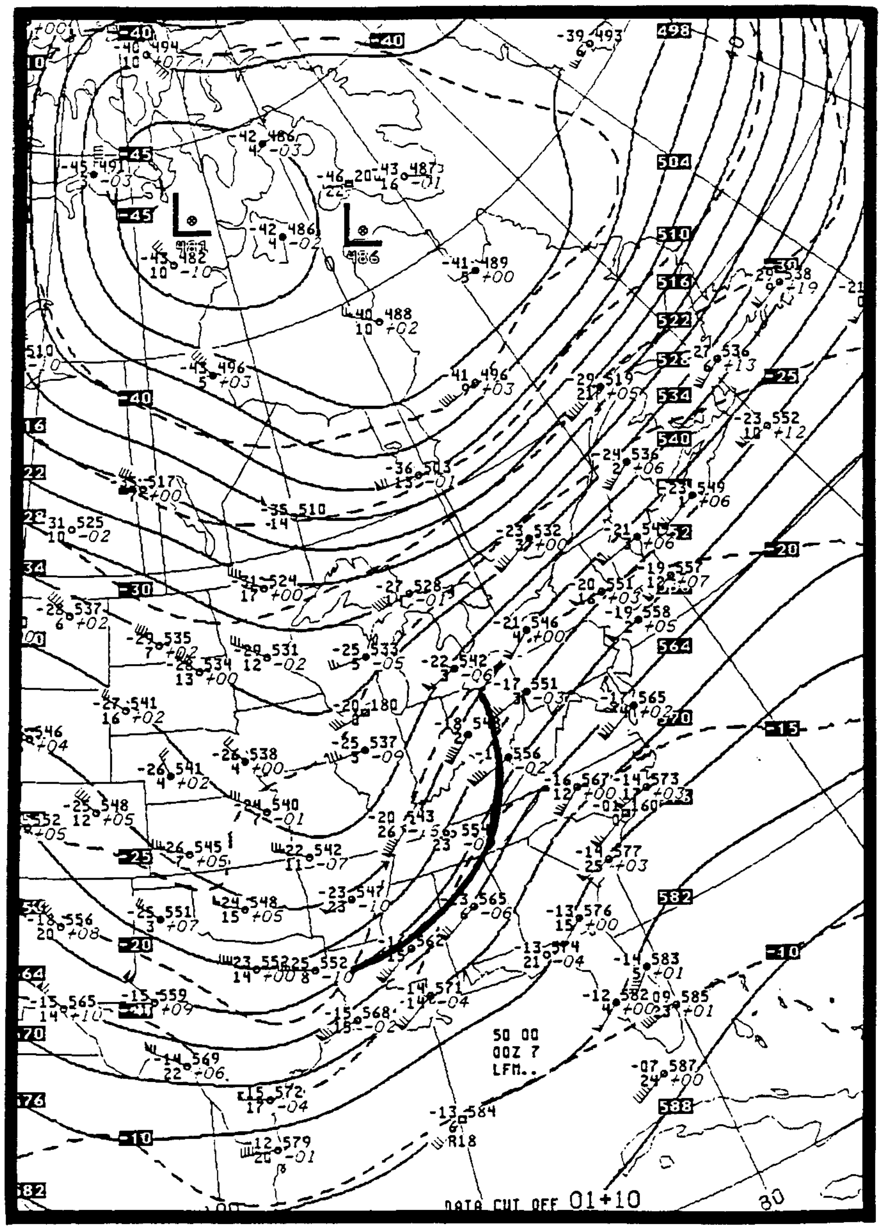


Figure 3.1.4 NMC 500 mb analysis for 0000 UTC 7 January 1995. The solid line represents the leading edge of cold advection.

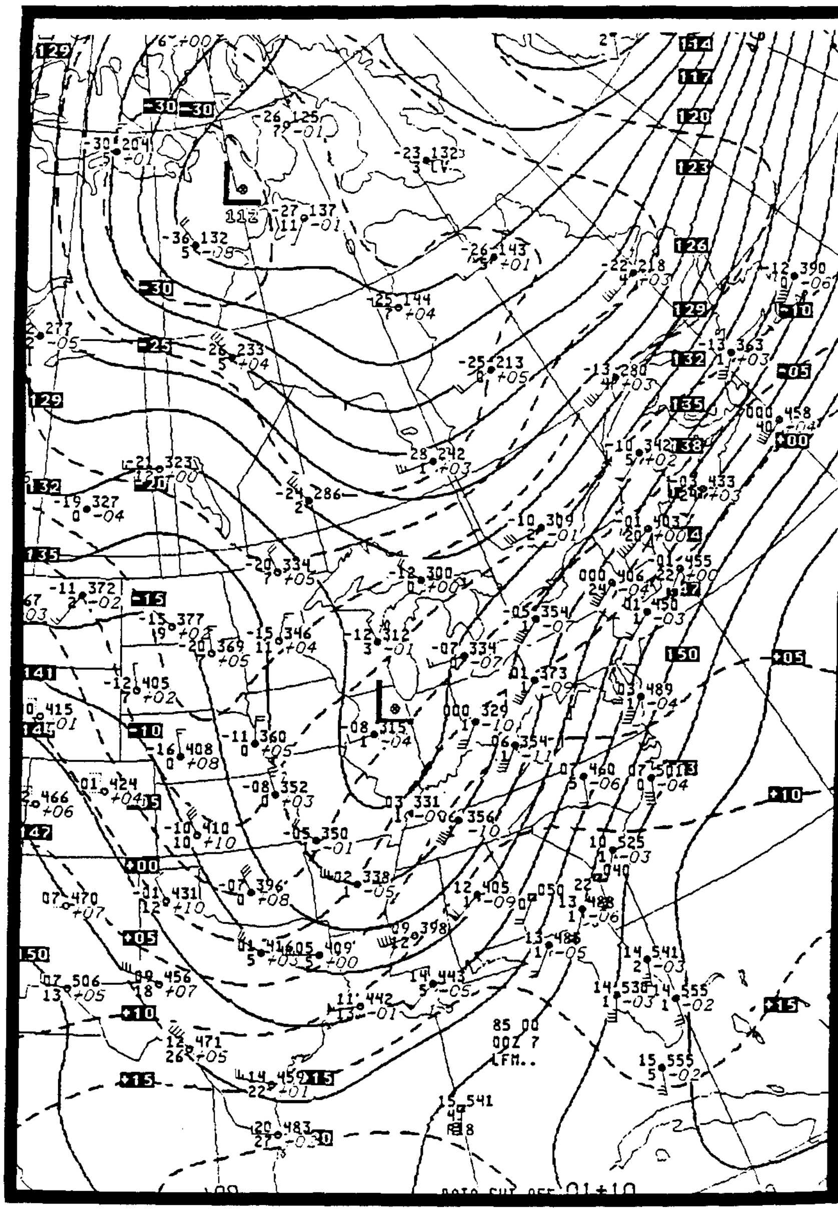


Figure 3.1.5 NMC 850 mb analysis for 0000 UTC 7 January 1995.

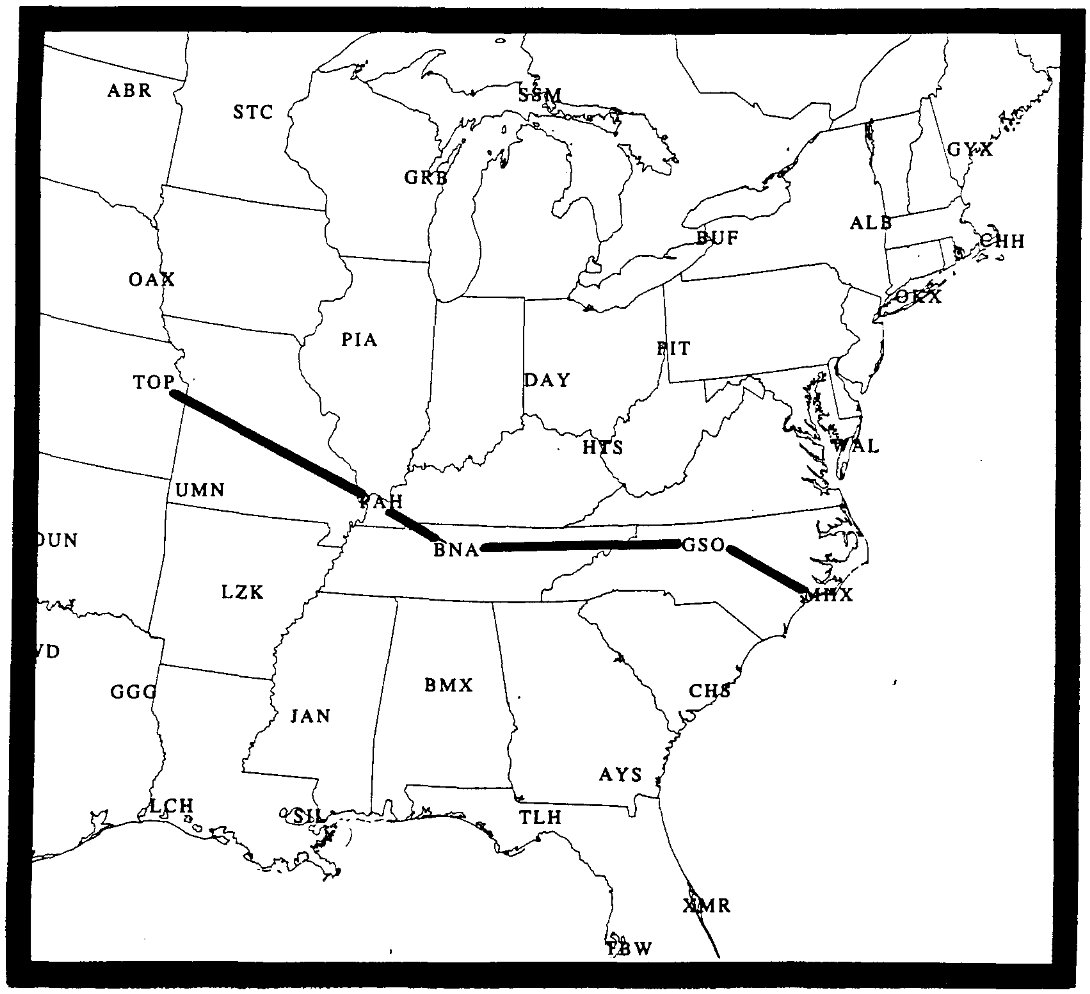


Figure 3.1.6. Track of cross section analyses (solid line).

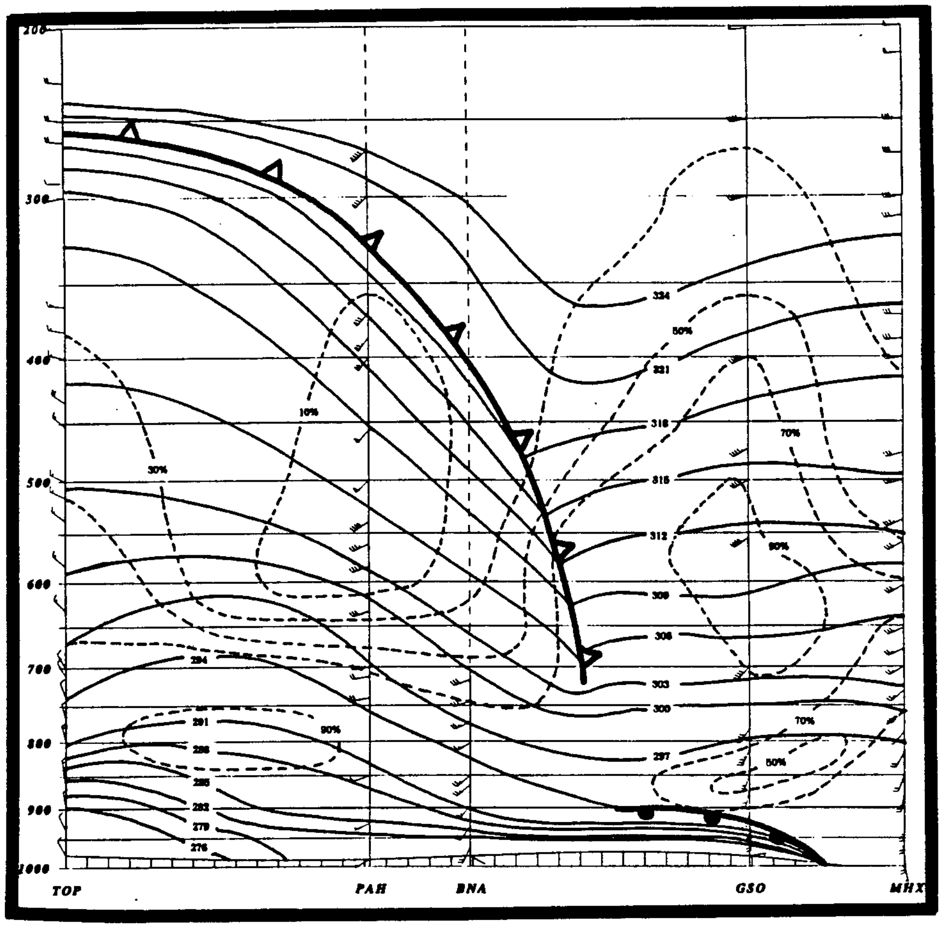


Figure 3.1.7a. Vertical cross-section through the CFA from Topeka, Kansas (TOP), to Paducah, Kentucky (PAH), to Nashville, Tennessee (BNA), to Greensboro, North Carolina (GSO), to Moorehead City, North Carolina (MHX) at 0000 UTC 7 January 1995. Solid lines are contours of potential temperature (θ) in ^{0}K labeled every 3 degrees. Dashed lines are relative humidity.

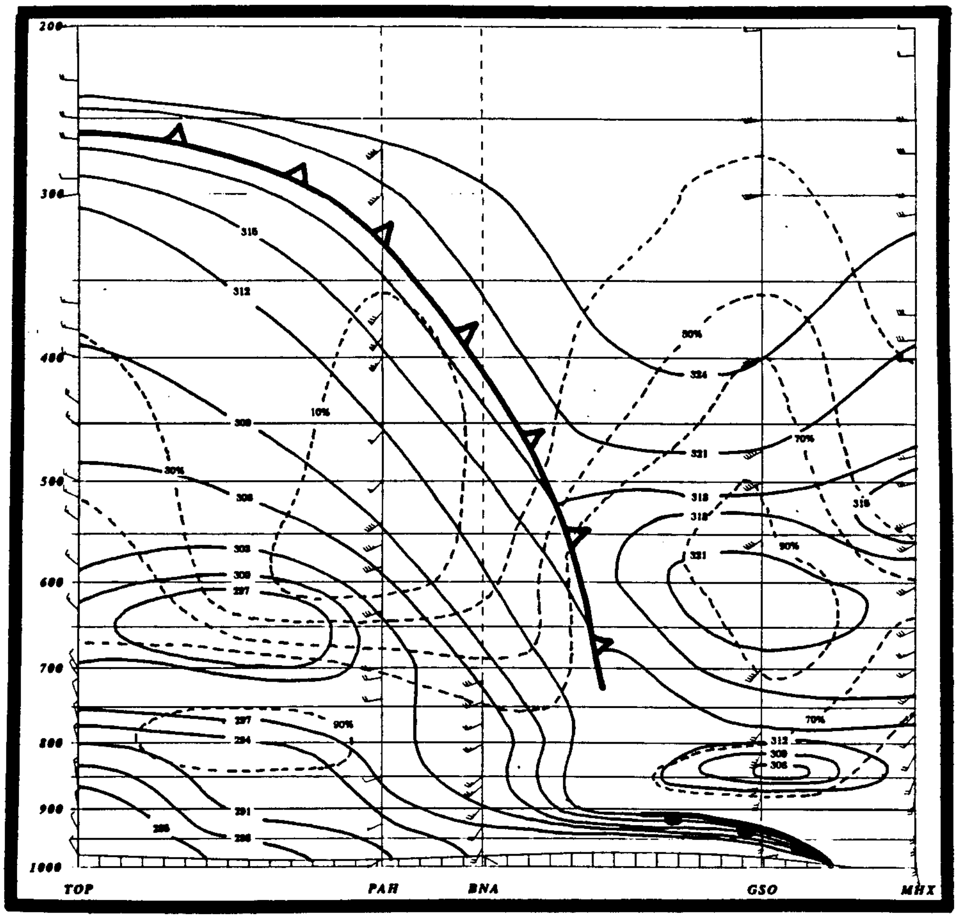


Figure 3.1.7b. Vertical cross-section through the CFA from Topeka, Kansas (TOP), to Paducah, Kentucky (PAH), to Nashville, Tennessee (BNA), to Greensboro, North Carolina (GSO), to Moorehead City, North Carolina (MHX) at 0000 UTC 7 January 1995. Solid lines are contours of equivalent potential temperature (θ_e) in ^{0}K labeled every 3 degrees. Dashed lines are relative humidity.

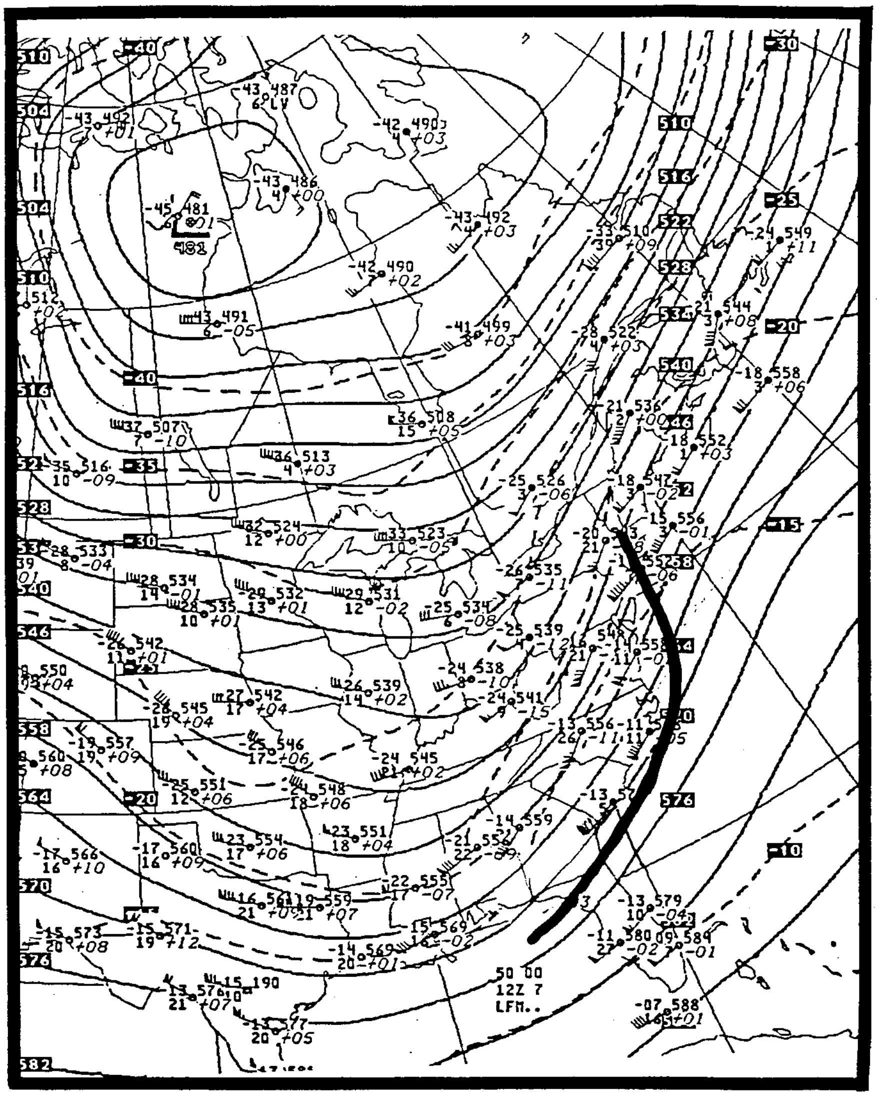


Figure 3.1.8. Same as Fig. 3.1.4 except for 1200 UTC 7 January 1995.

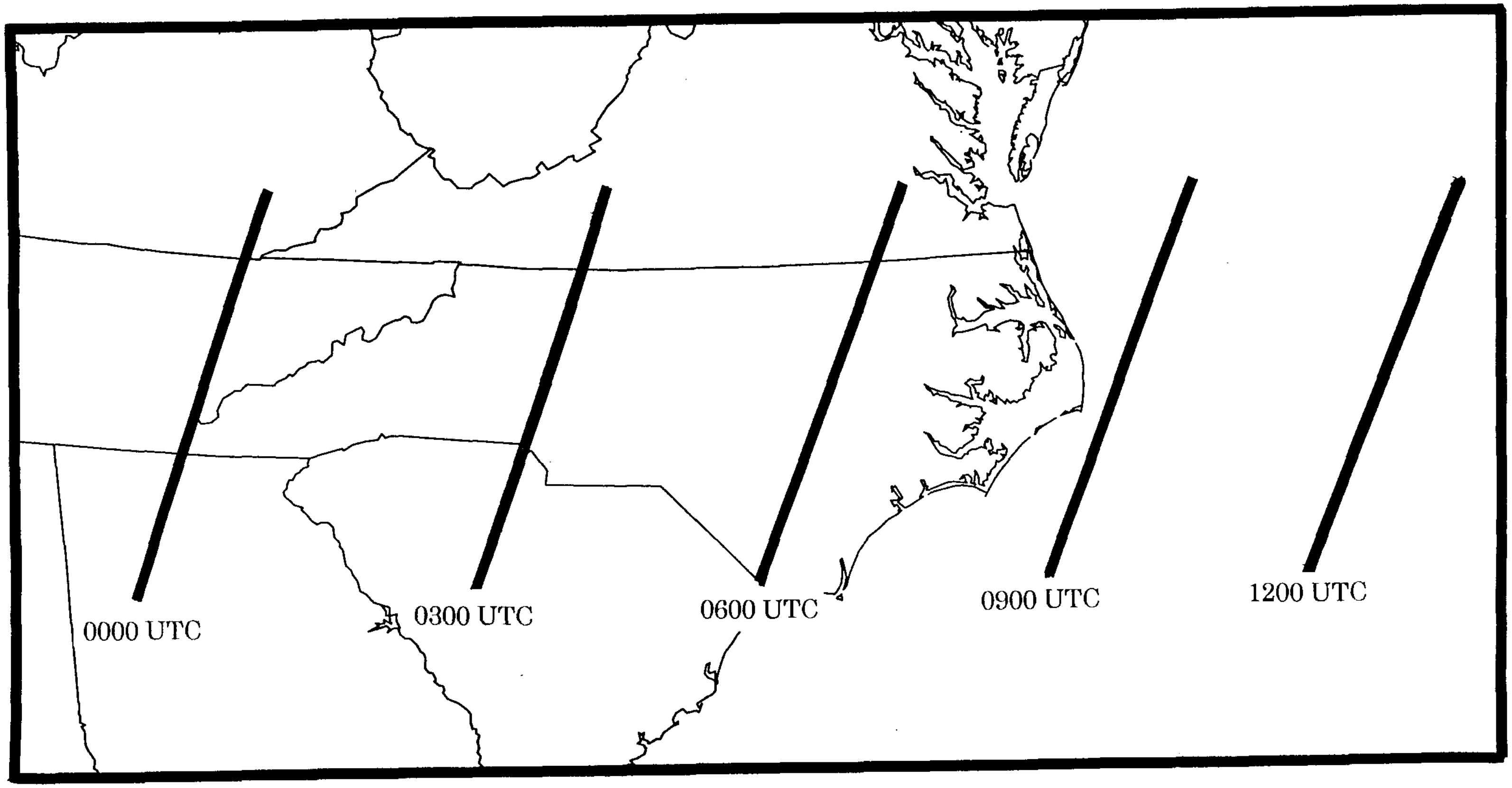


Figure 3.1.9. Location of CFA at 500 mb interpolated between 0000 UTC and 1200 UTC 7 January 1995 locations.

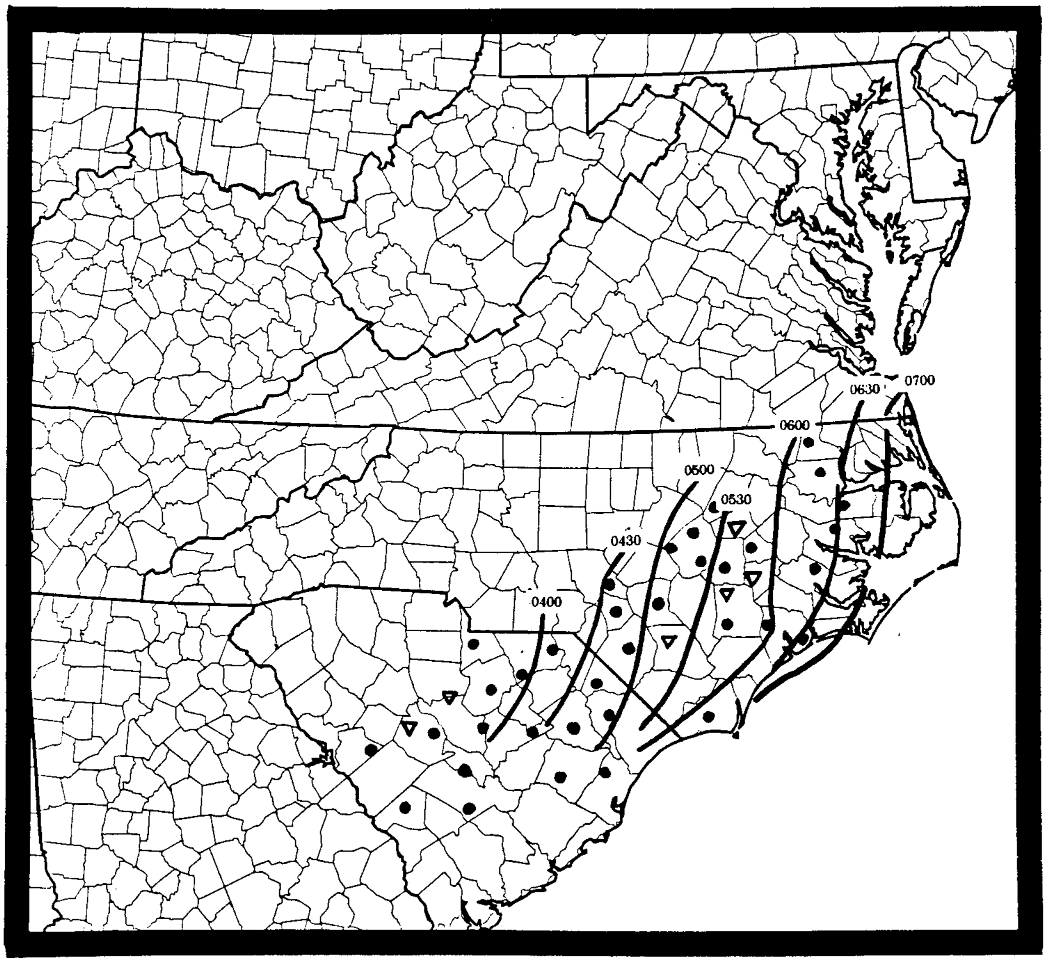


Figure 3.1.10. Wind damage and tornado reports from North and South Carolina for 6-7 January 1995. Damaging winds depicted by circles (•), tornadoes depicted by triangles (∇). Solid line represents squall line movement with time of each postition denoted above each line.

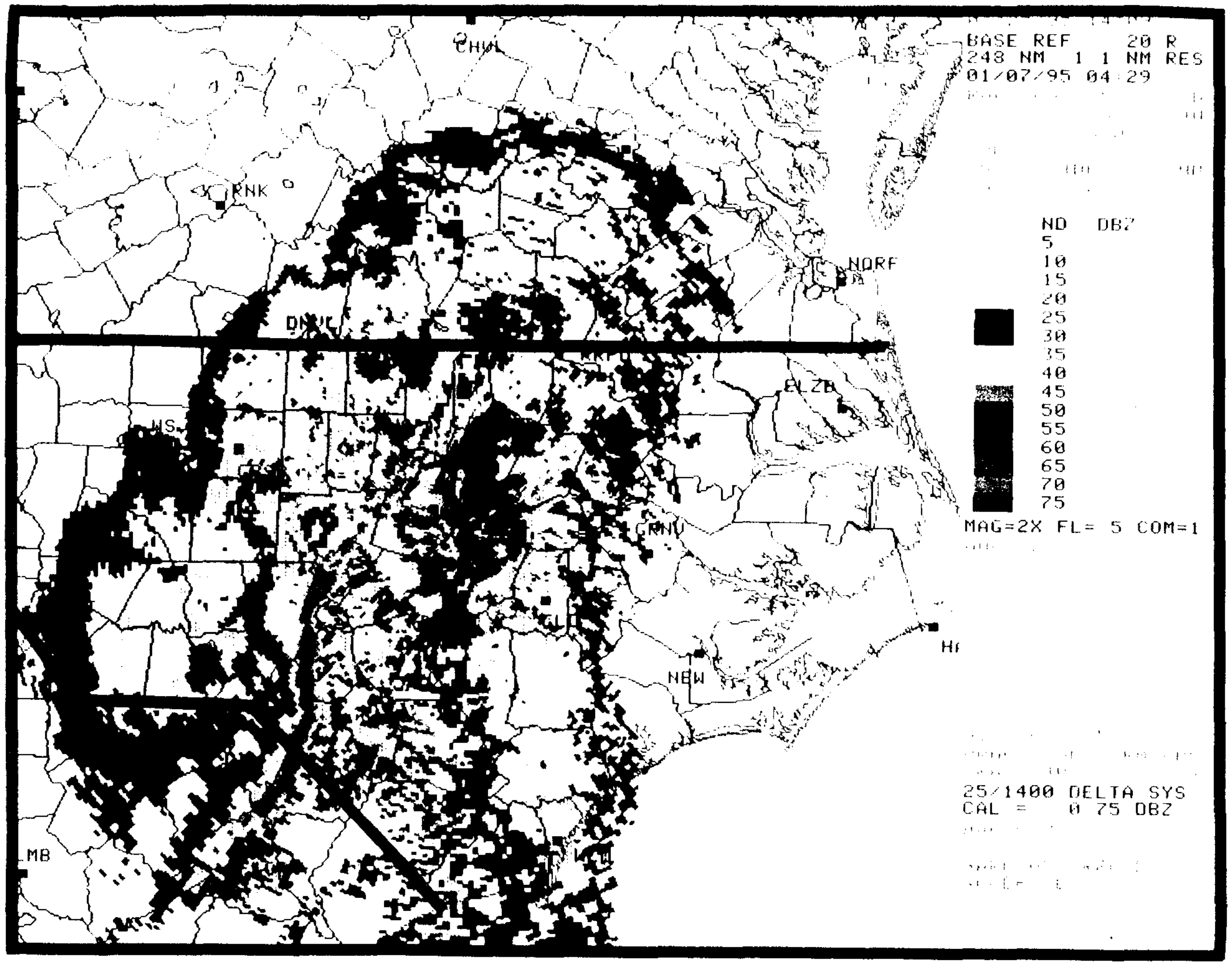


Figure 3.1.11. WSR-88D reflectivity image from Raleigh, North Carolina for 0430 UTC 7 January 1995.

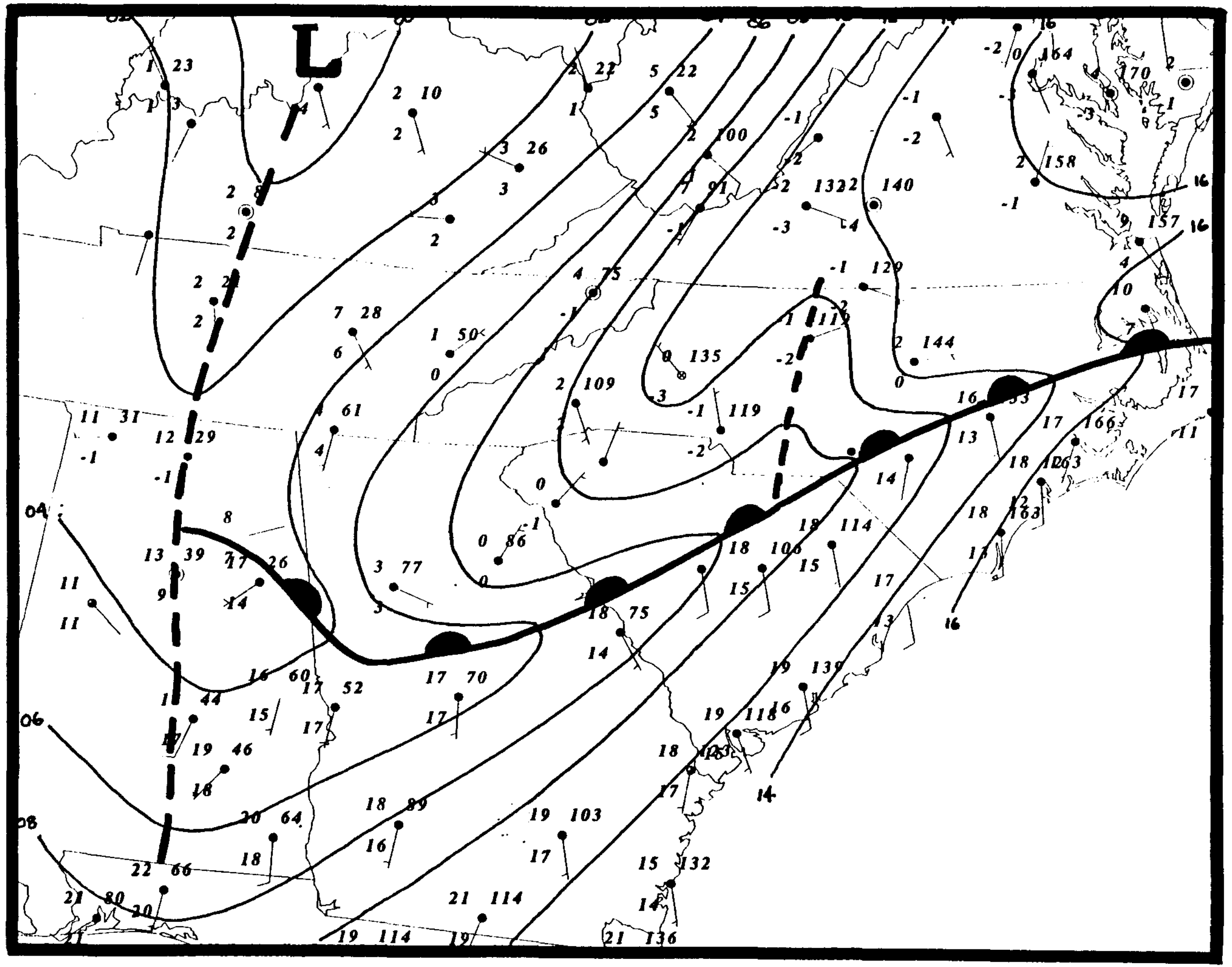


Figure 3.2.1. Subjective surface analysis for 0000 UTC 7 January 1995. Surface reporting stations are shown along with 2 mb isobars.

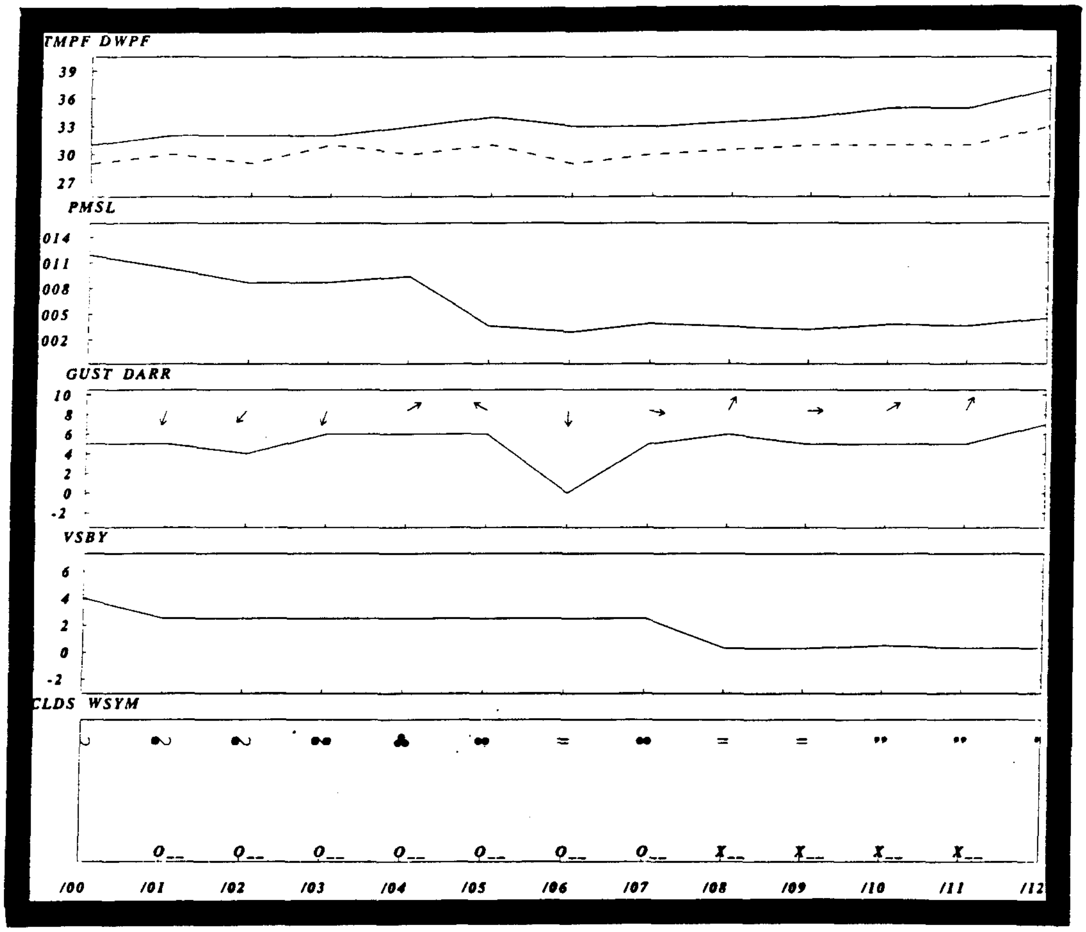


Figure 3.2.2. Surface meteogram for Greensboro, North Carolina from 0000 - 1200 UTC 7 January 1995. Top panel shows temperature (solid line) and dewpoint (dashed line) in °F. Second panel shows surface pressure in millibars. Third panel depicts wind gusts in knots (solid line) and direction (arrows). Fourth panel shows visibility in miles. Bottom panel shows current weather.

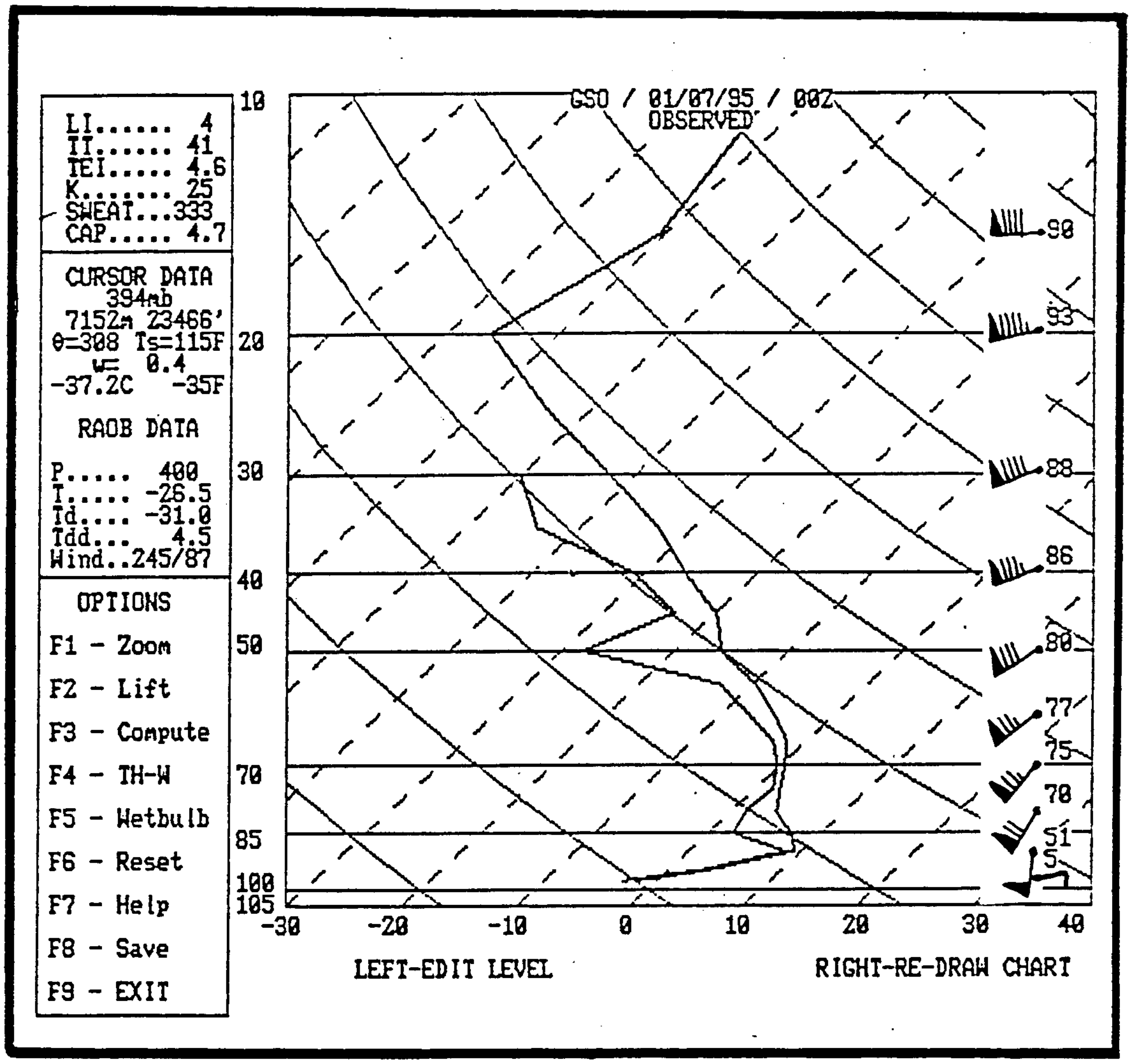


Figure 3.2.3. 0000 UTC 7 January 1995 skew T-log p plot of Greensboro, North Carolina (GSO), rawinsonde observation. Stability indicies given in upper left corner of image.

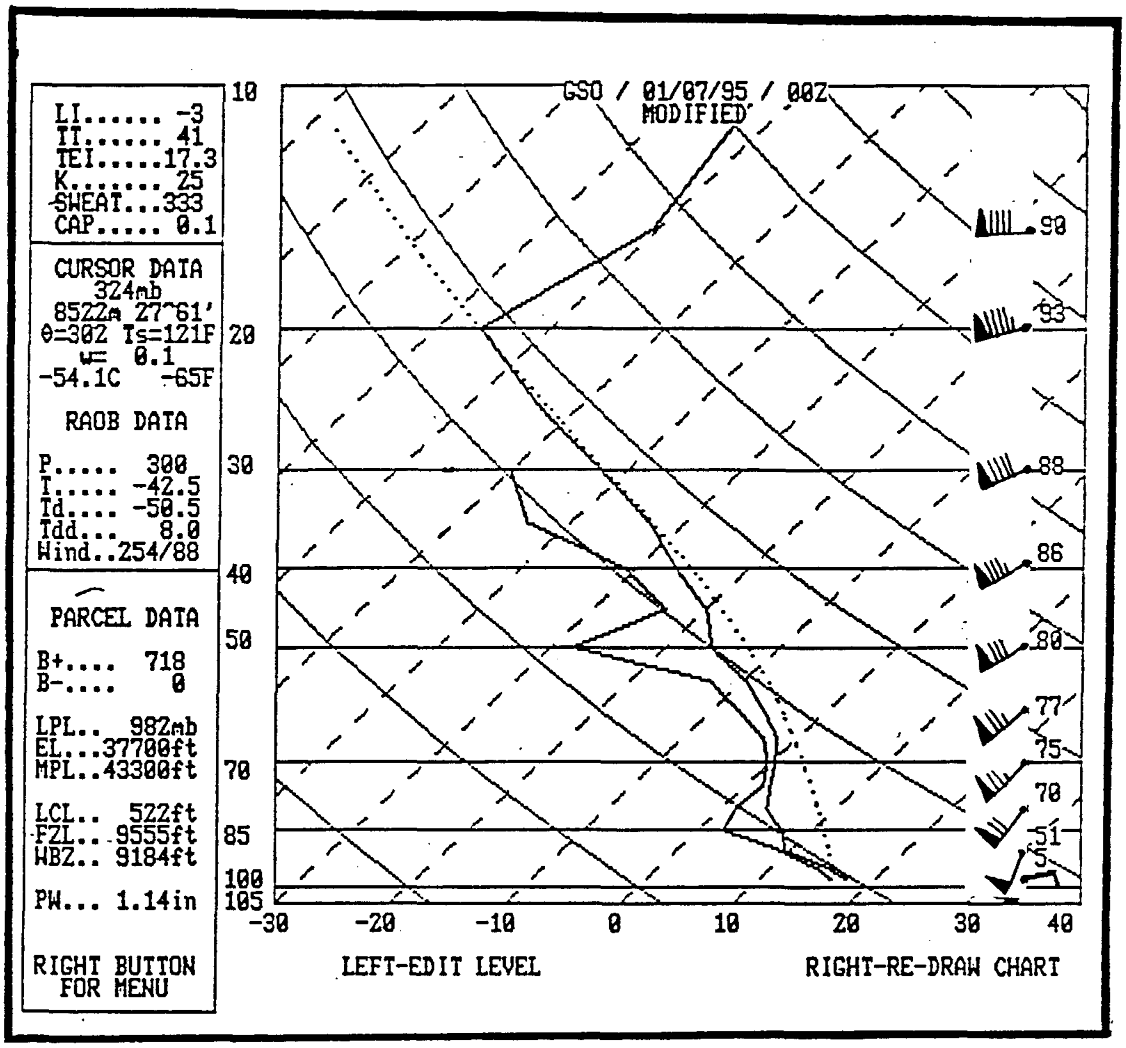


Figure 3.2.4. Same as Fig. 3.2.3 except lower 100 mb modified to reflect surface data from 0000 UTC 7 January 1995 at Fayetville, North Carolina.

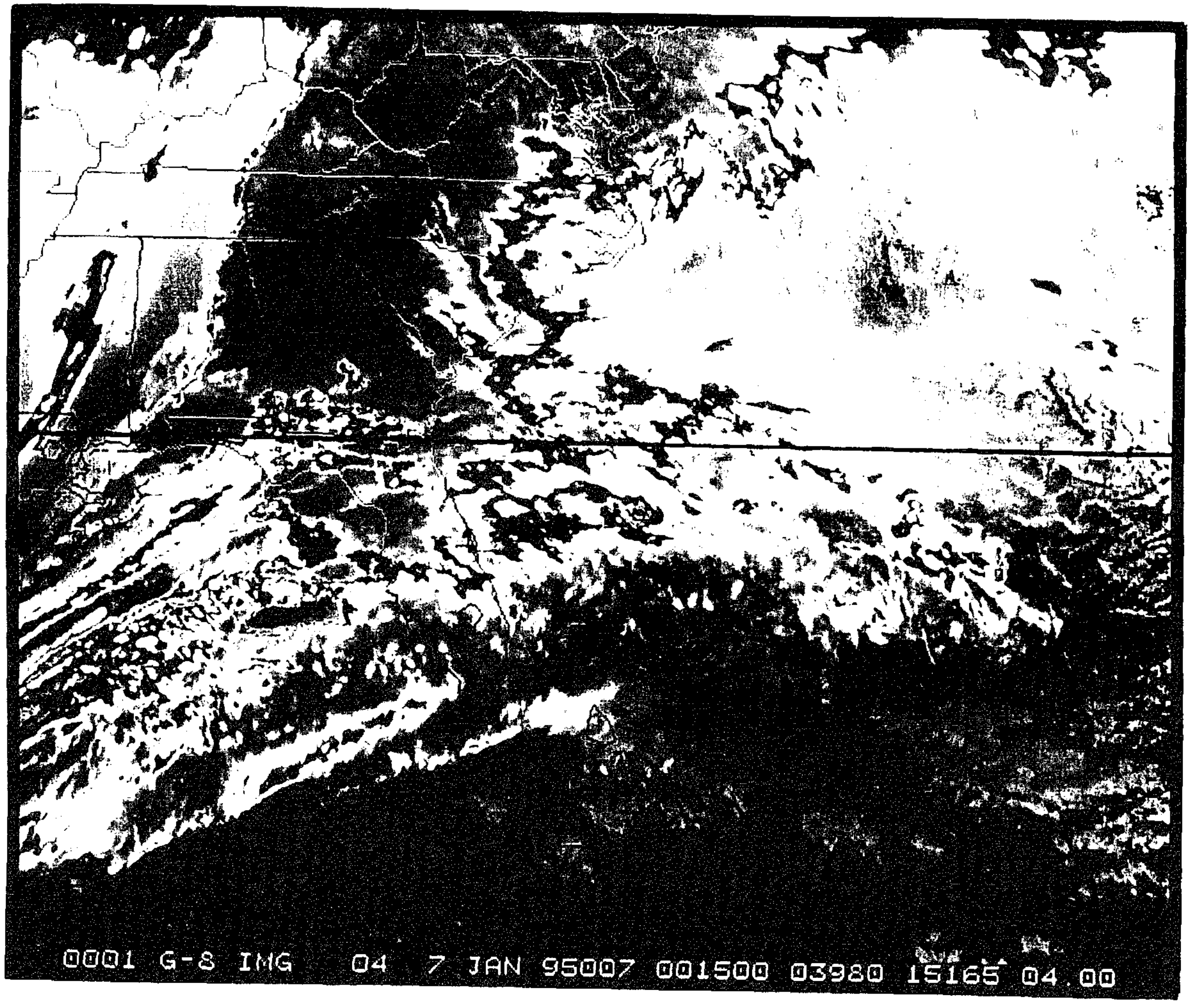


Figure 3.2.5. Infrared satellite imagery for 0000 UTC 7 January 1995.

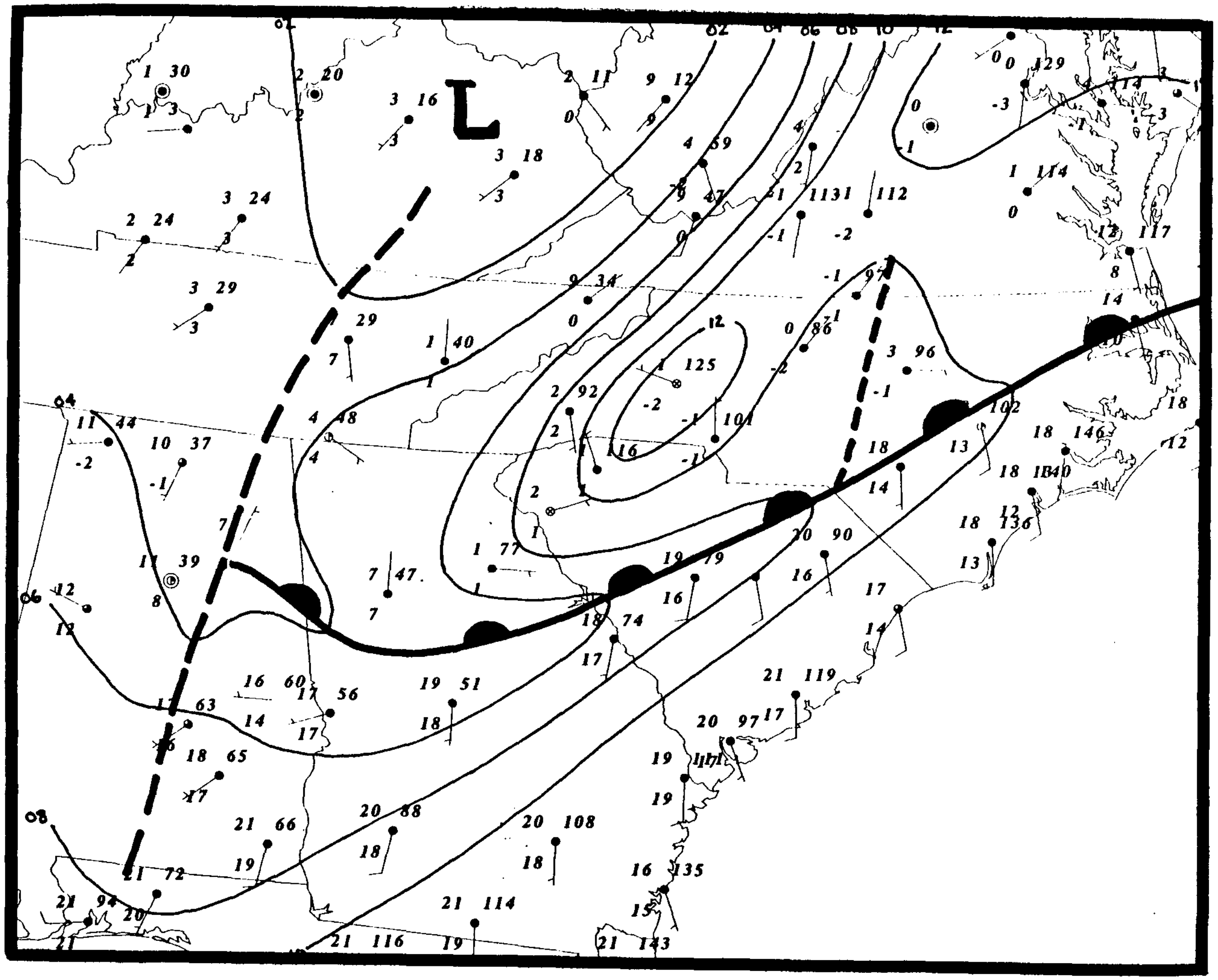


Figure 3.2.6. Same as Fig. 3.2.1 except for 0200 UTC 7 January 1995.

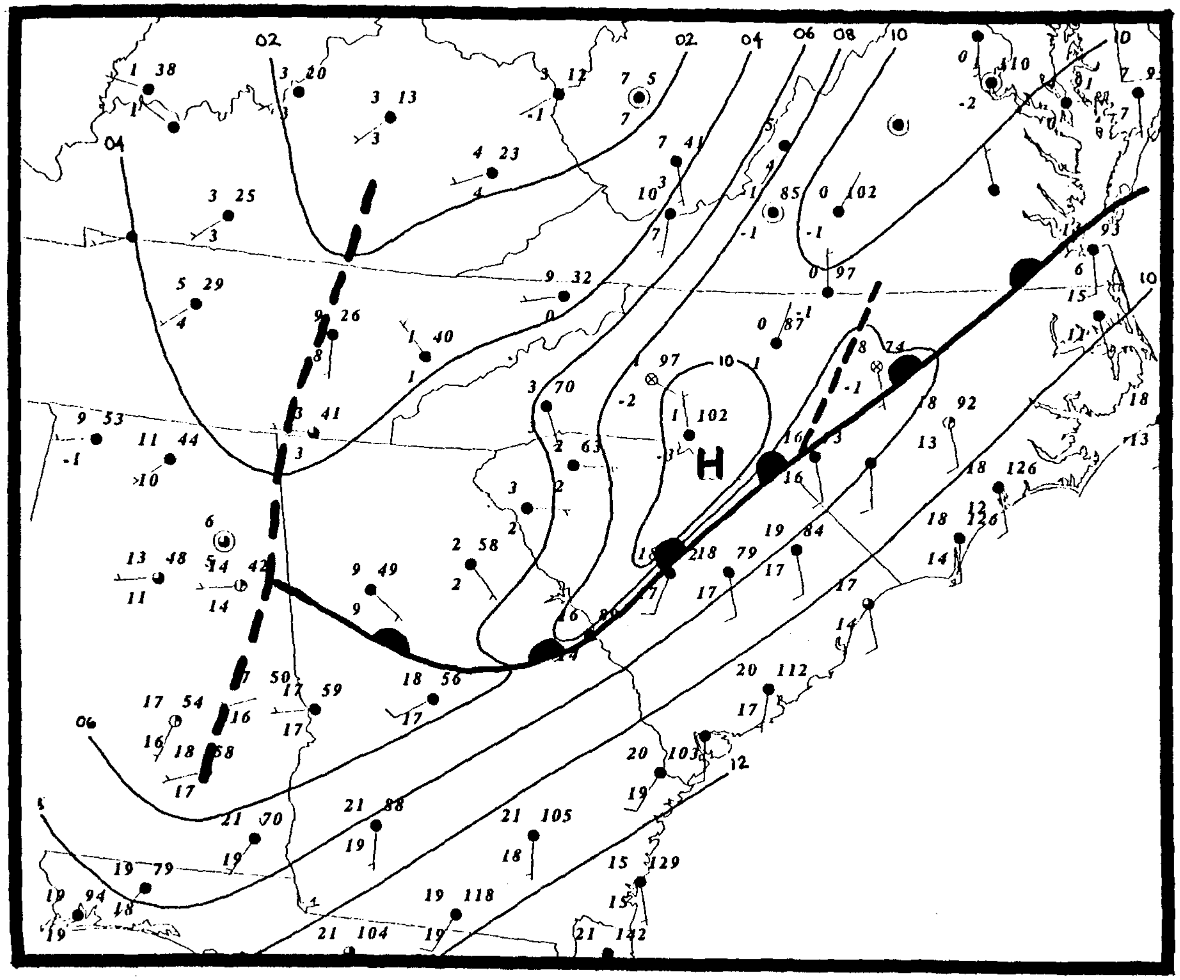


Figure 3.2.7. Same as Fig. 3.2.1 except for 0300 UTC 7 January 1995.

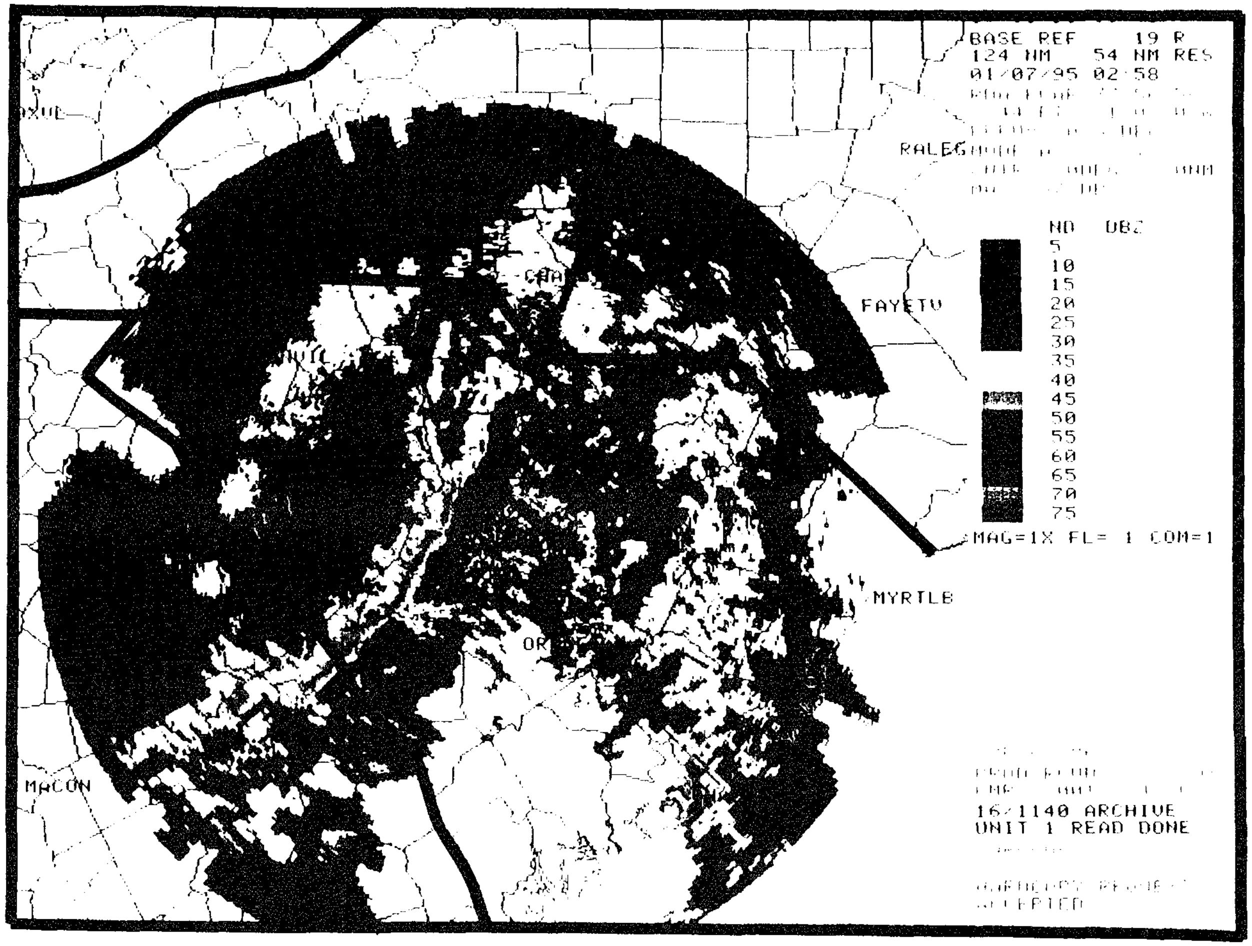


Figure 3.2.8a. WSR-88D reflectivity image from Columbia, South Carolina for 0258 UTC 7 January 1995. Frontal boundary is subjectively analyzed for comparison with squall line location.

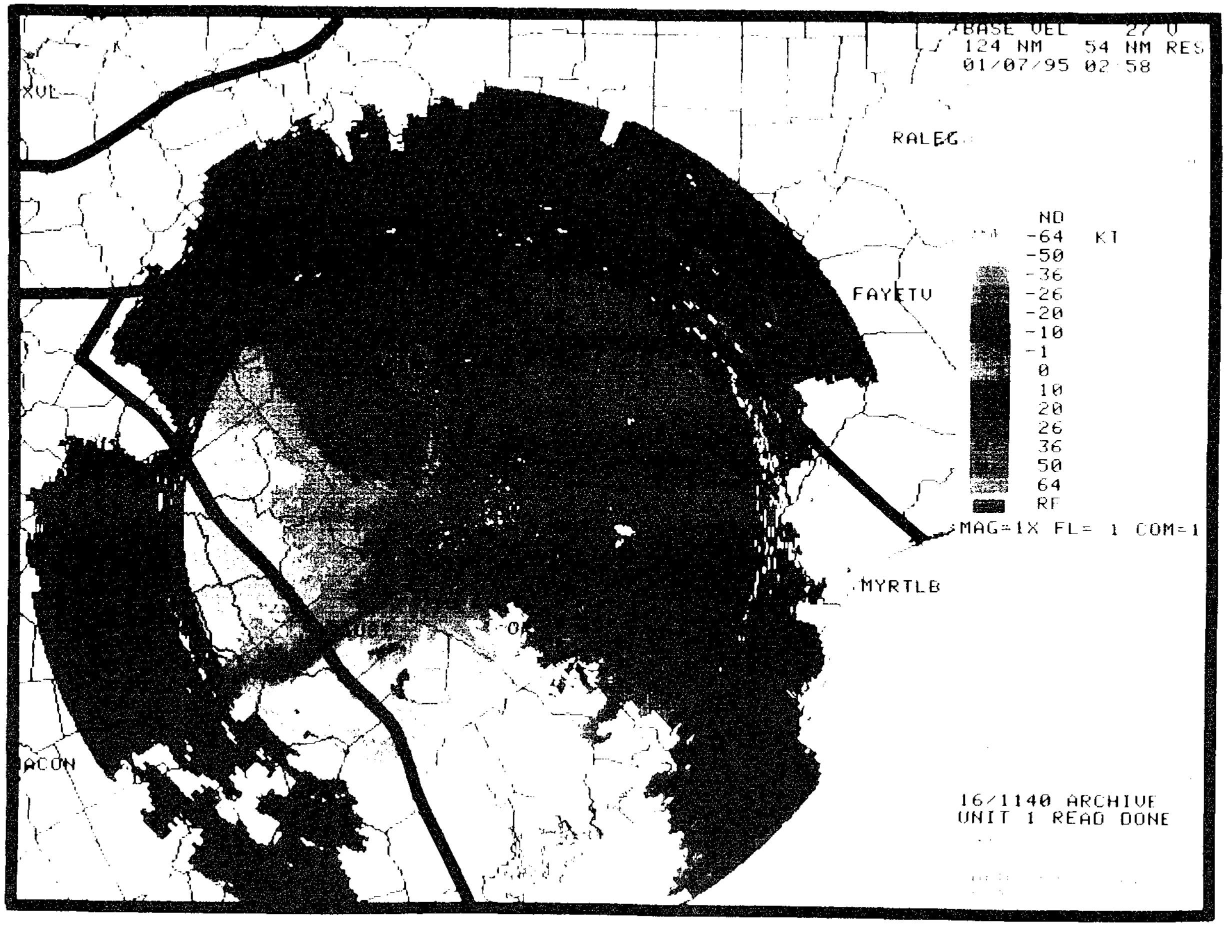


Figure 3.2.8b. WSR-88D velocity image from Columbia, South Carolina for 0258 UTC 7 January 1995. Frontal boundary is subjectively analyzed for comparison with squall line location.

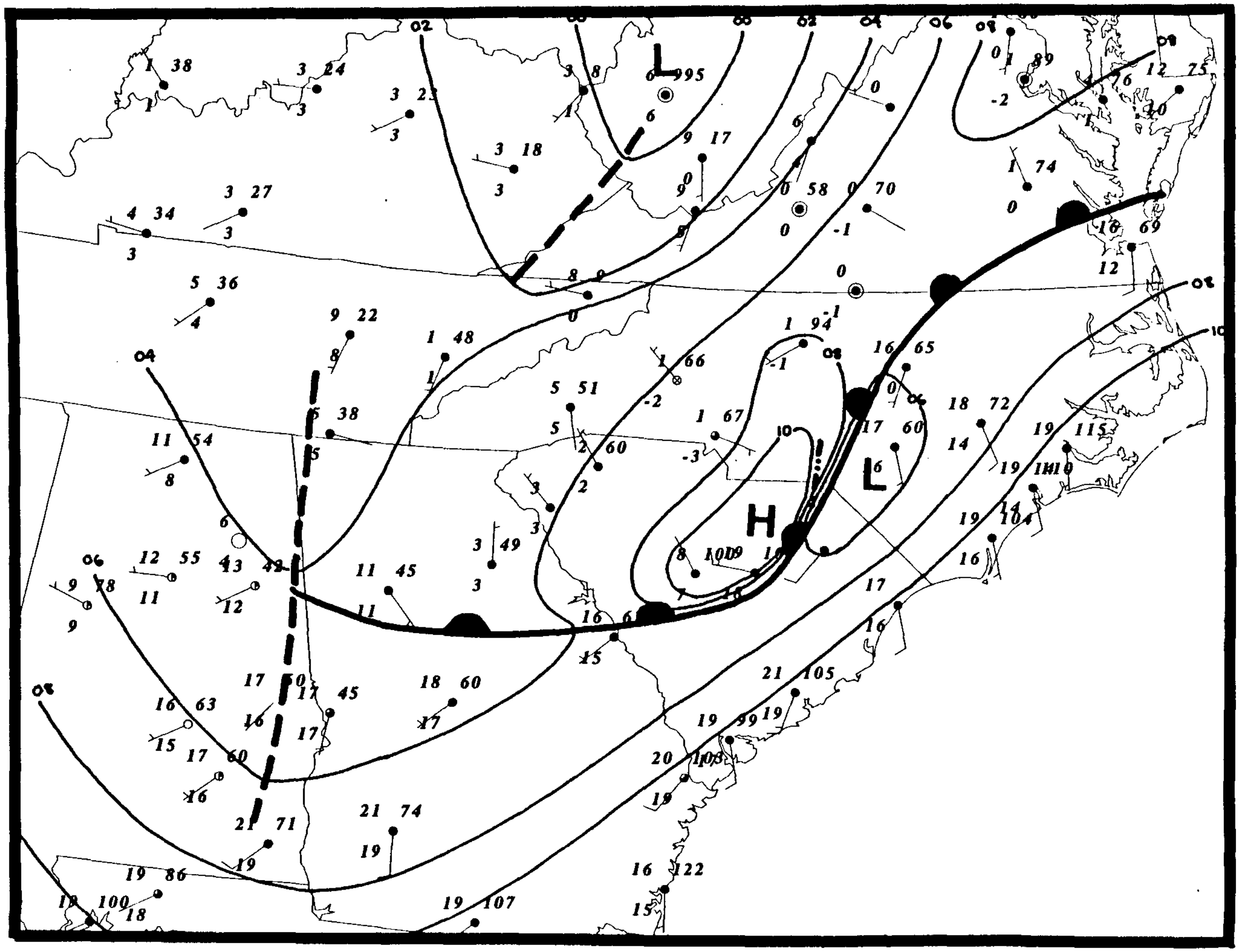


Figure 3.2.9. Same as Fig. 3.2.1 except for 0400 UTC 7 January 1995.

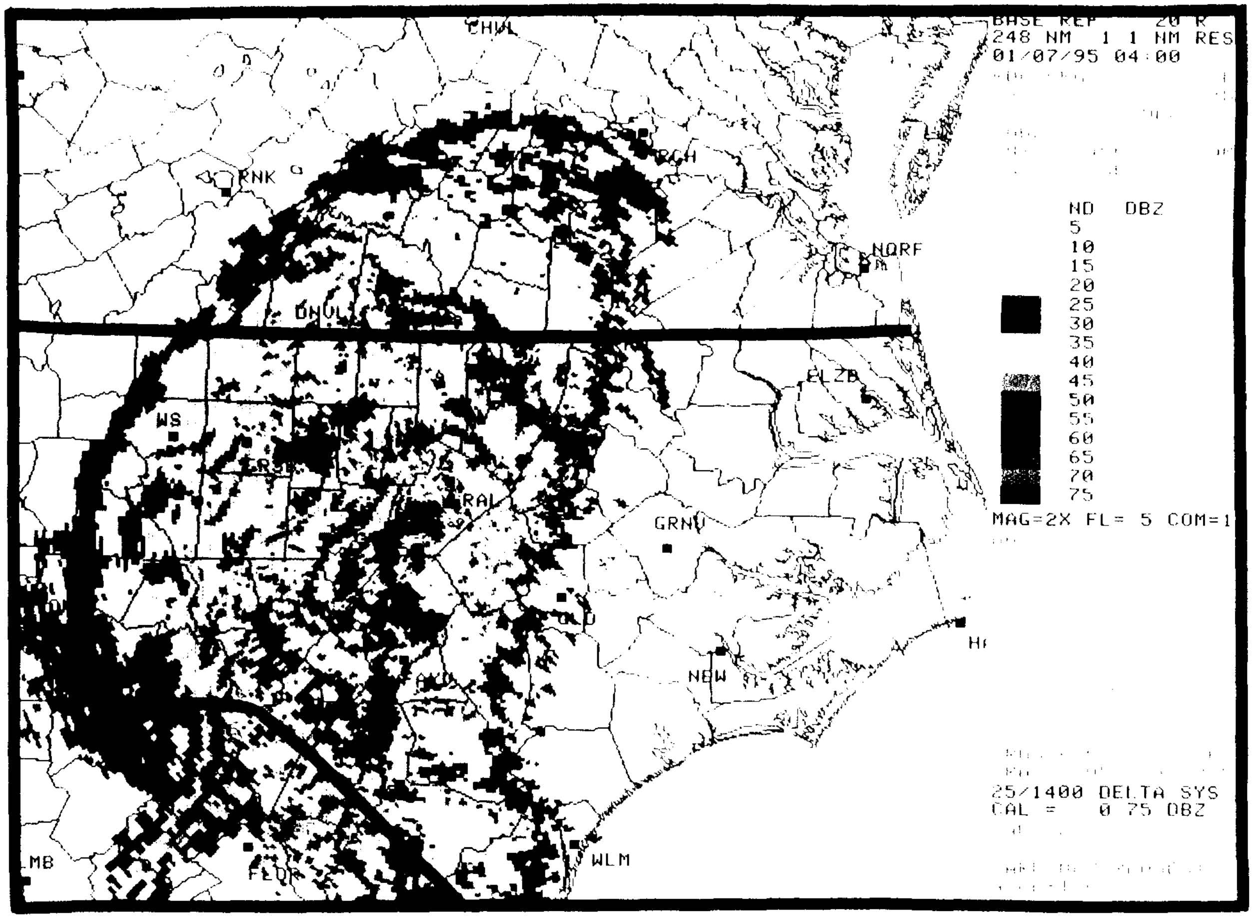


Figure 3.2.10. WSR-88D reflectivity image from Raleigh, North Carolina for 0400 UTC 7 January 1995.

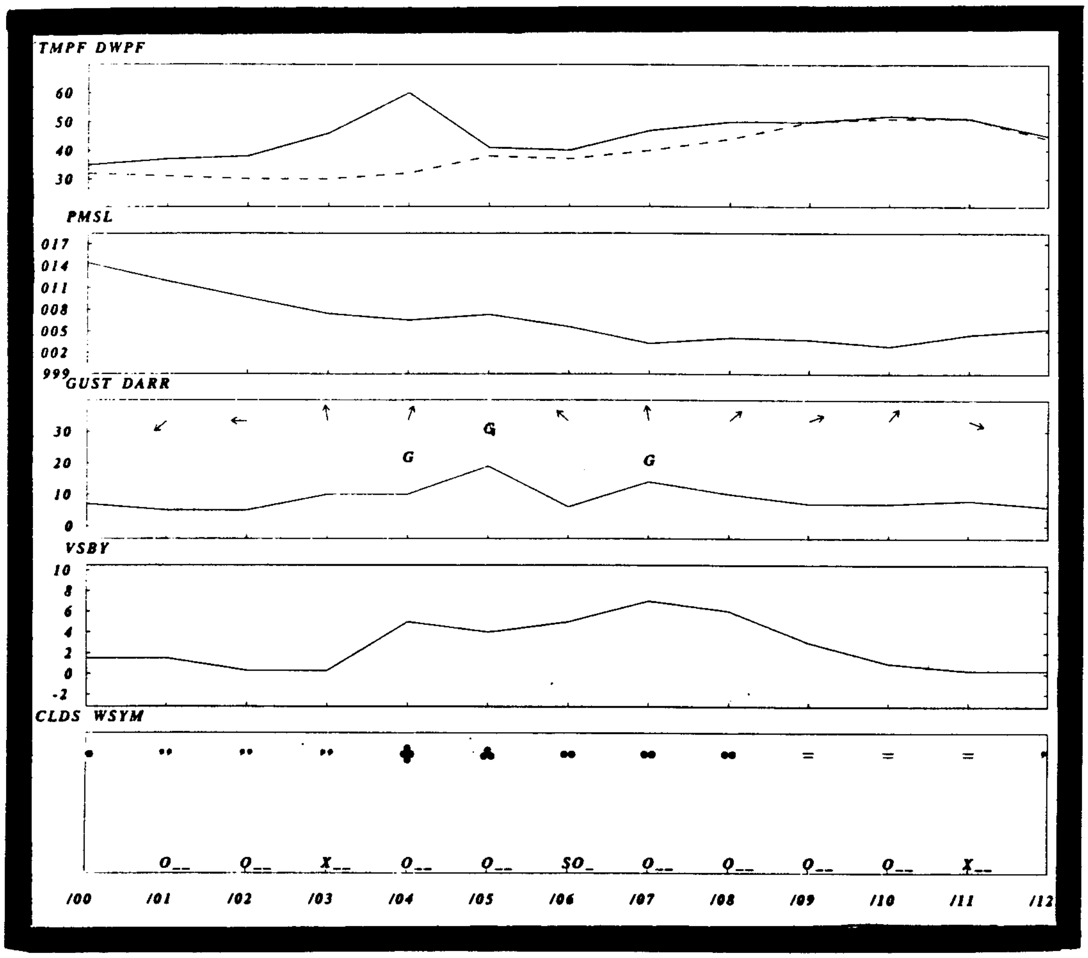


Figure 3.2.11. Same as Fig. 3.2.2 except for Raleigh, North Carolina.

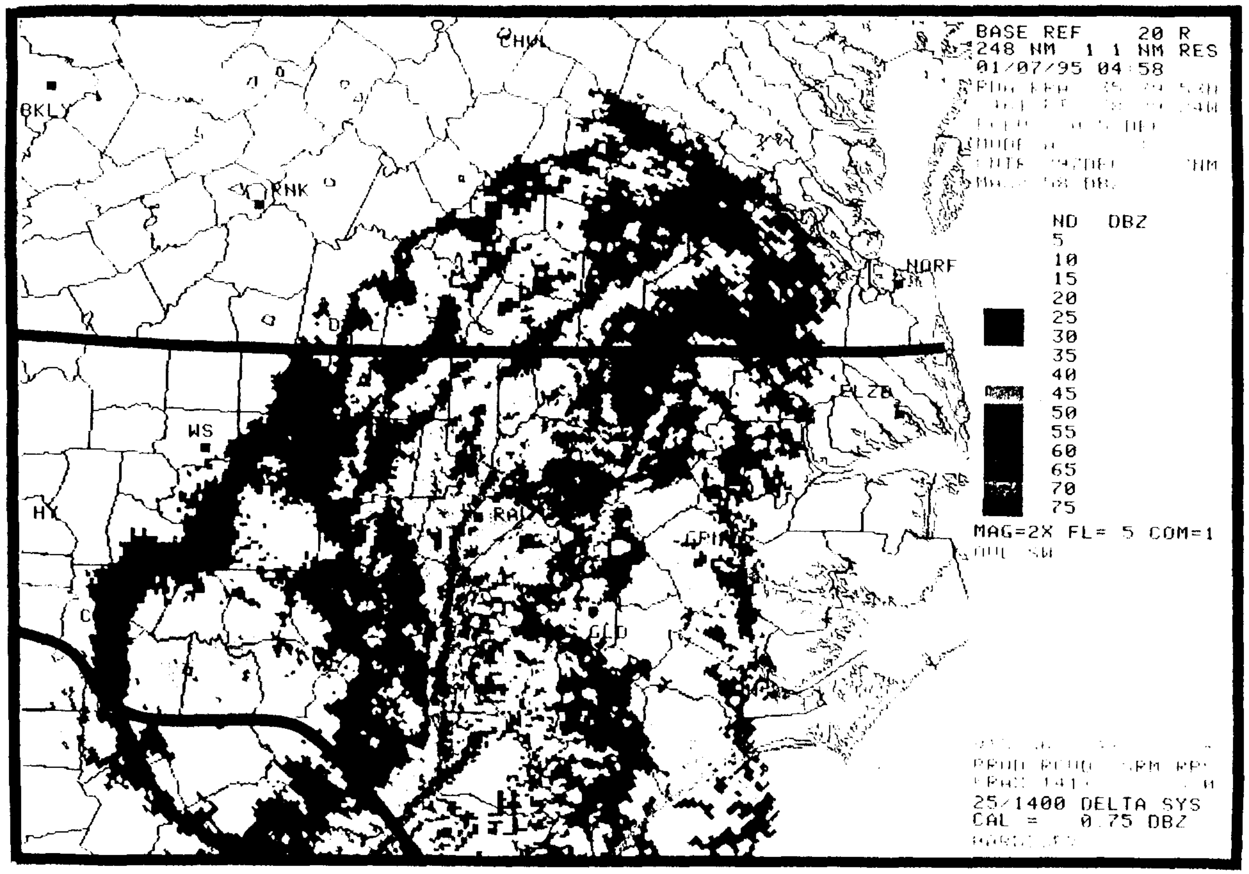


Figure 3.2.12. Same as Fig. 3.2.10 except for 0458 UTC 7 January 1995.

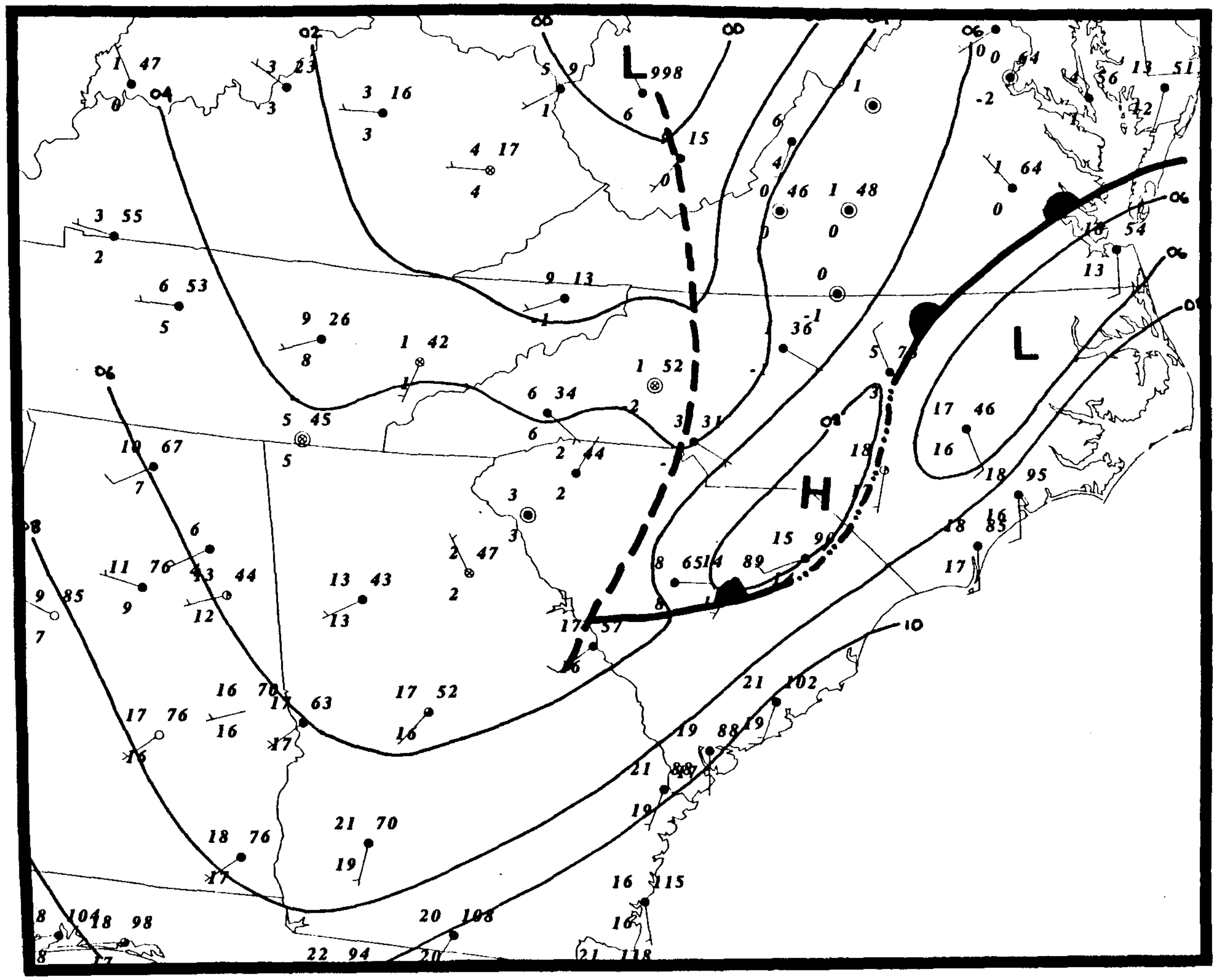


Figure 3.2.13. Same as Fig. 3.2.1 except for 0500 UTC 7 January 1995.

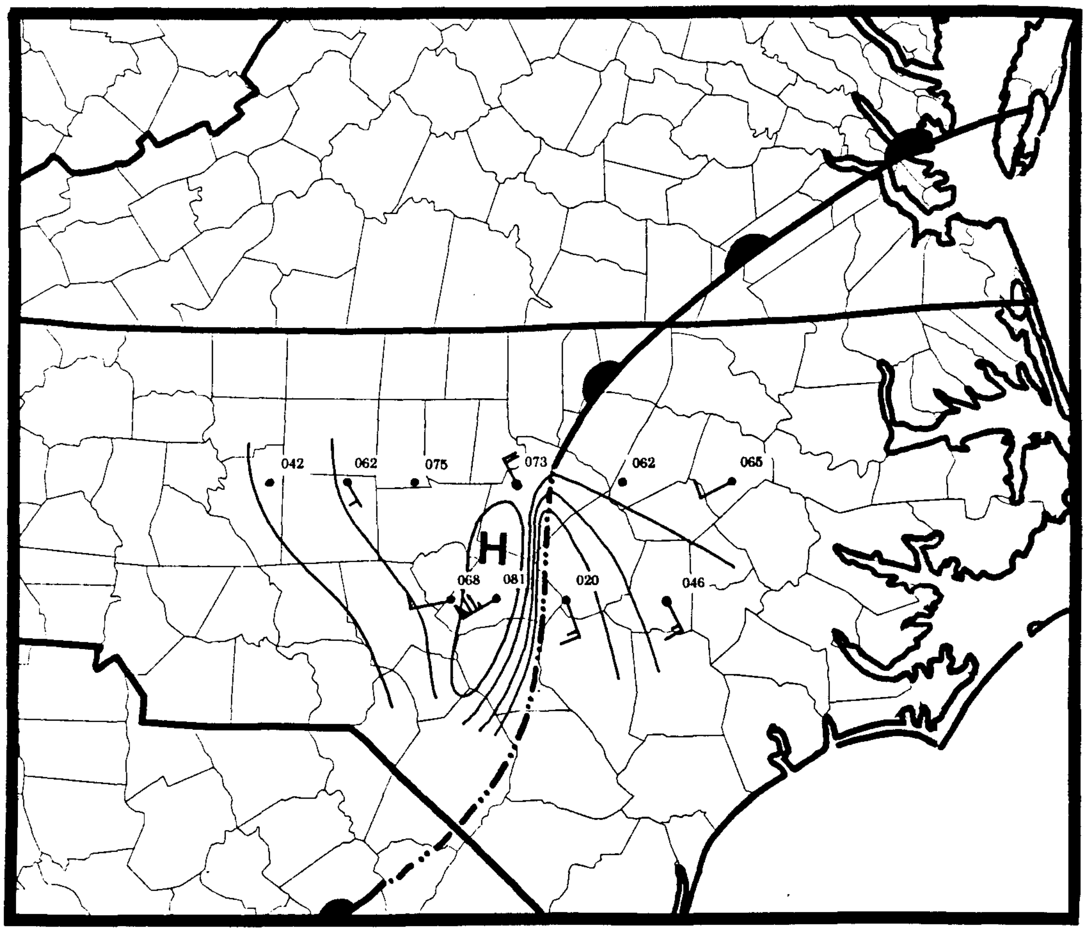


Figure 3.2.14. Time to space analysis for 0450 UTC 7 January 1995 across central North Carolina. Observations are plotted with standard wind barbs and pressure. Thin lines represent subjective pressure analysis. Dot and dash line is leading edge of the squall line.

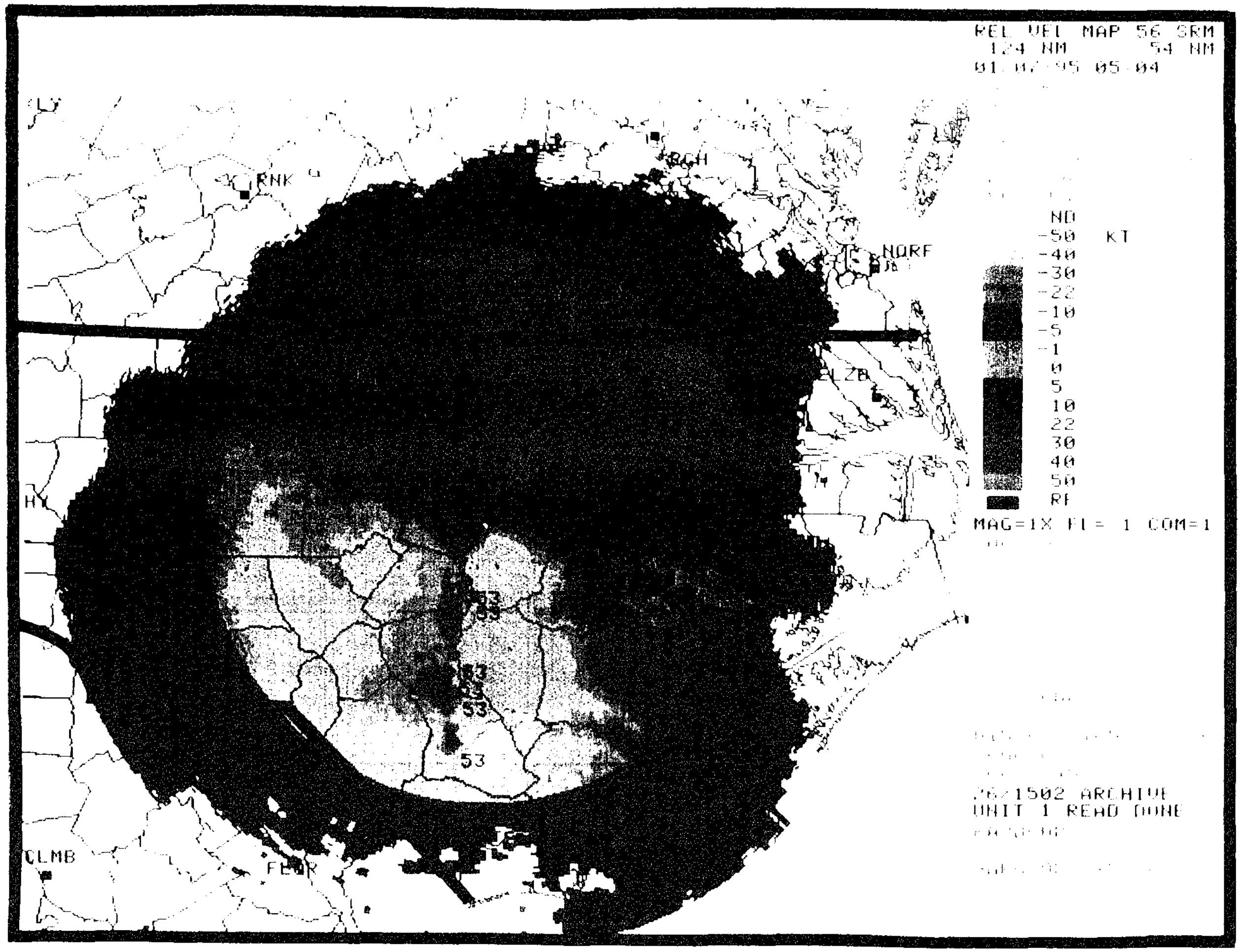


Figure 3.2.15. WSR-88D velocity image from Raleigh, North Carolina for 0504 UTC 7 January 1995.

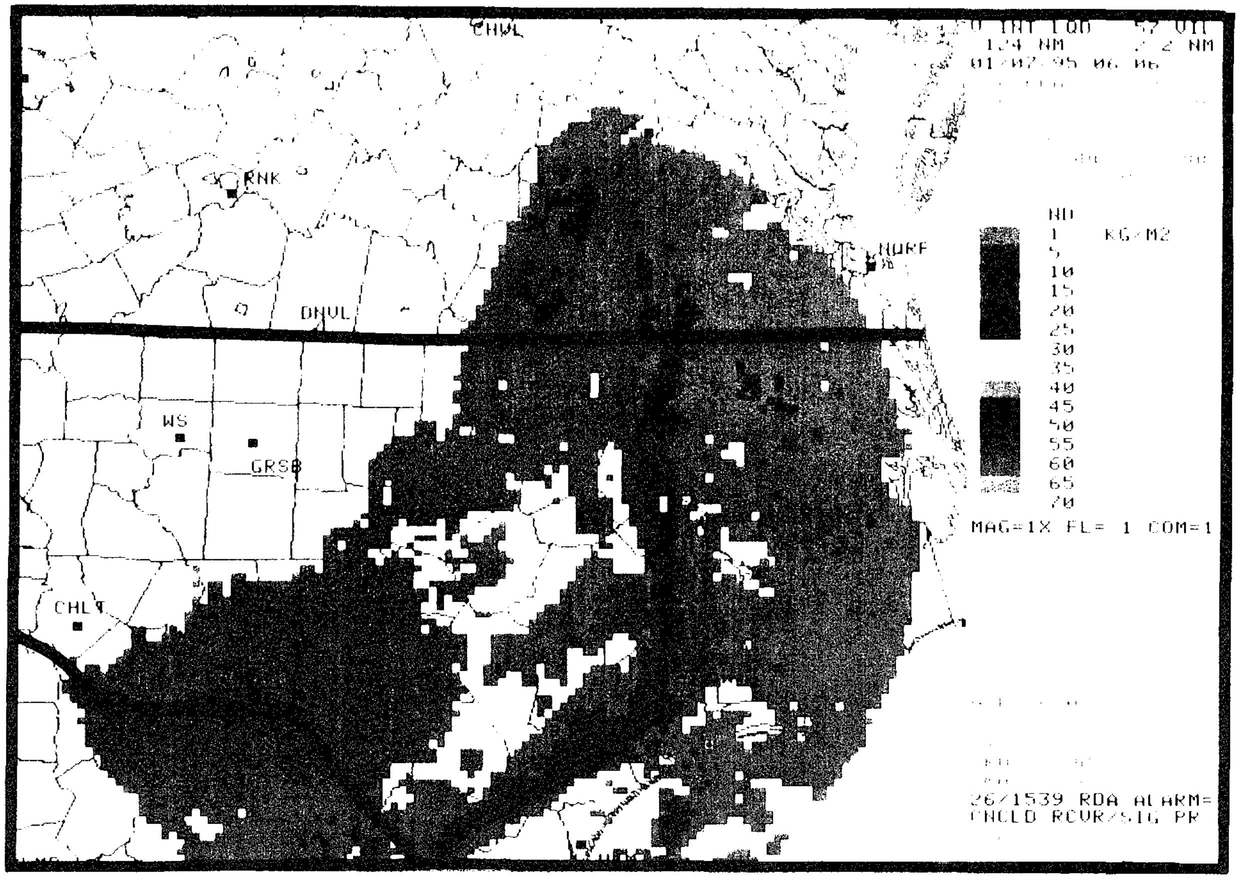
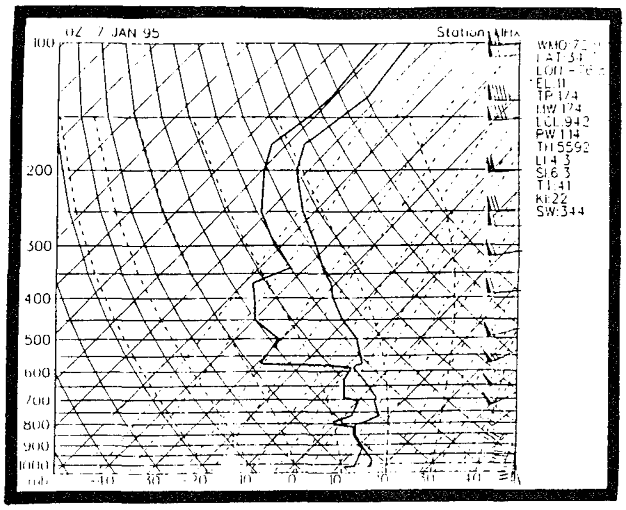
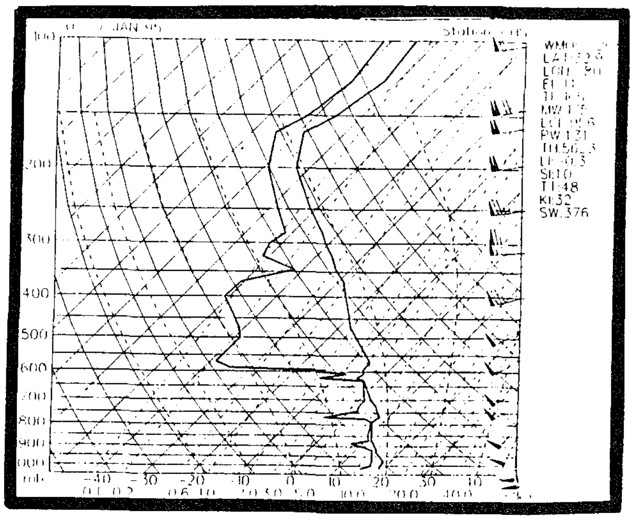


Figure 3.2.16. WSR-88D Vertically Integrated Liquid (VIL) image from Raleigh, North Carolina for 0606 UTC 7 January 1995.



A



B

Figure 3.2.17 a and b. Upper air soundings from 0000 UTC 7 January 1995 for A) Morehead City, North Carolina and B) Charleston, South Carolina.

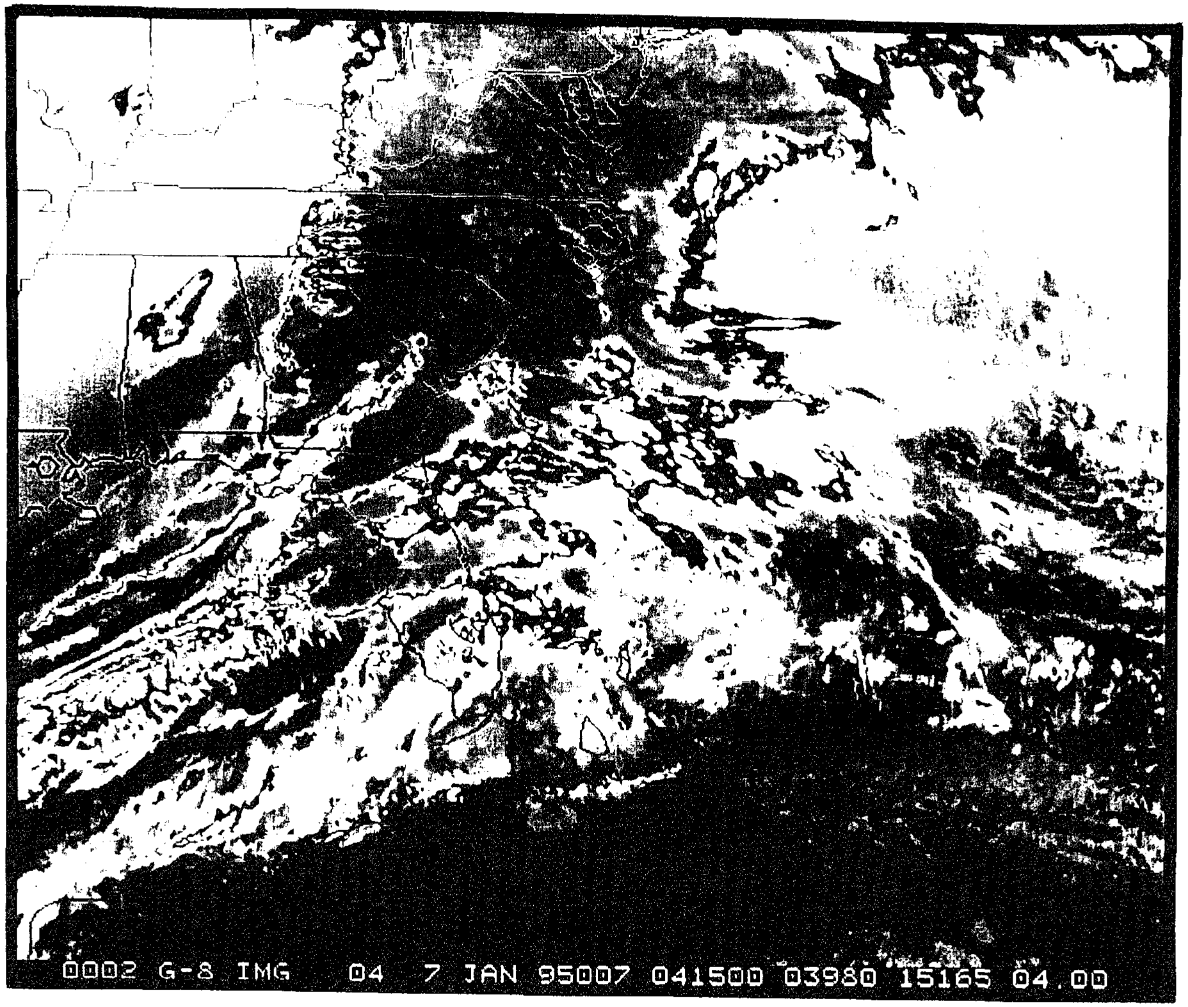


Figure 3.2.18. Infrared satellite imagery for 0400 UTC 7 January 1995.

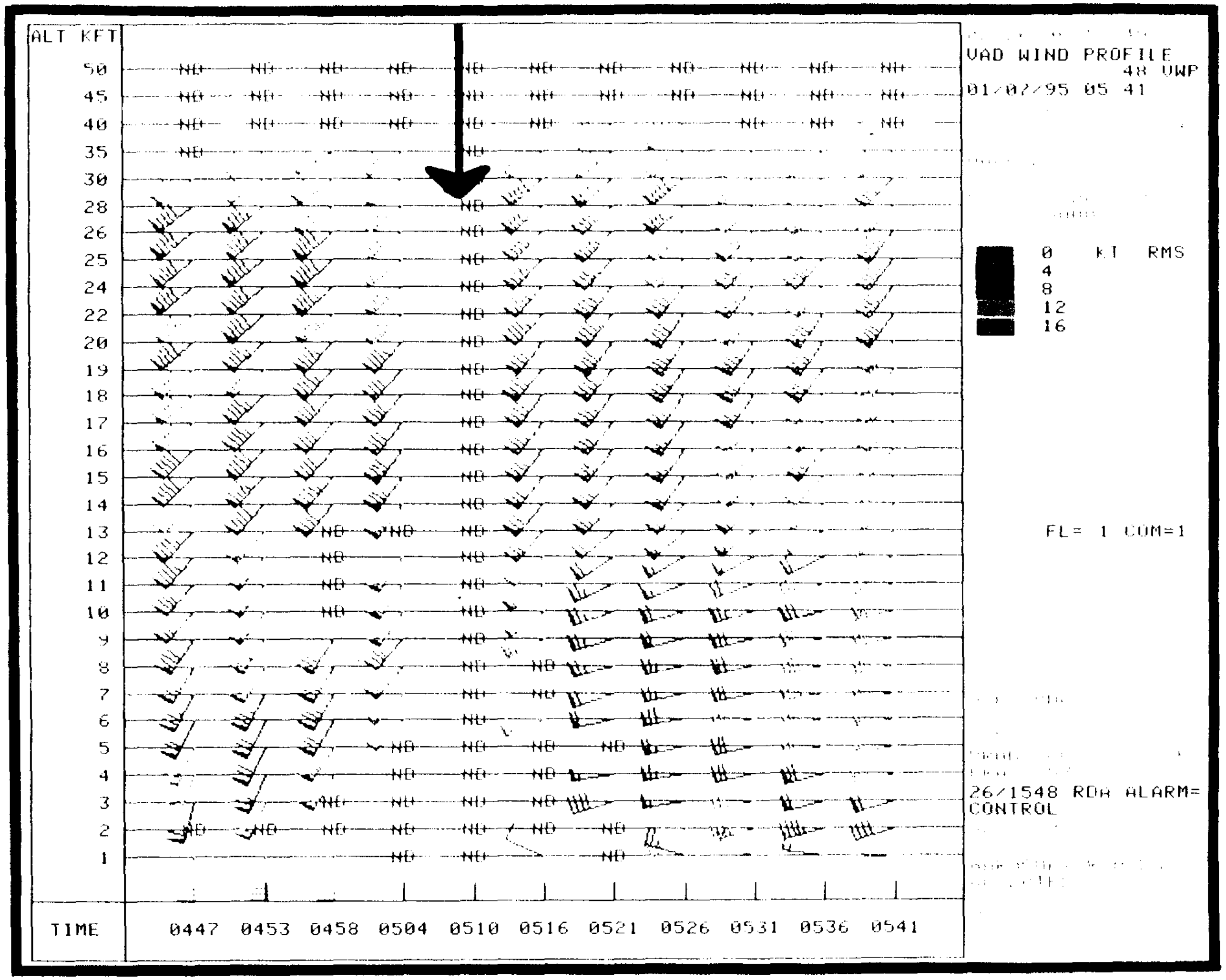


Figure 3.2.20. WSR-88D Velocity Azimuth Display (VAD) wind profile from Raleigh, North Carolina for 0349-0541 UTC 7 January 1995. Arrow represents the time of squall line passage.

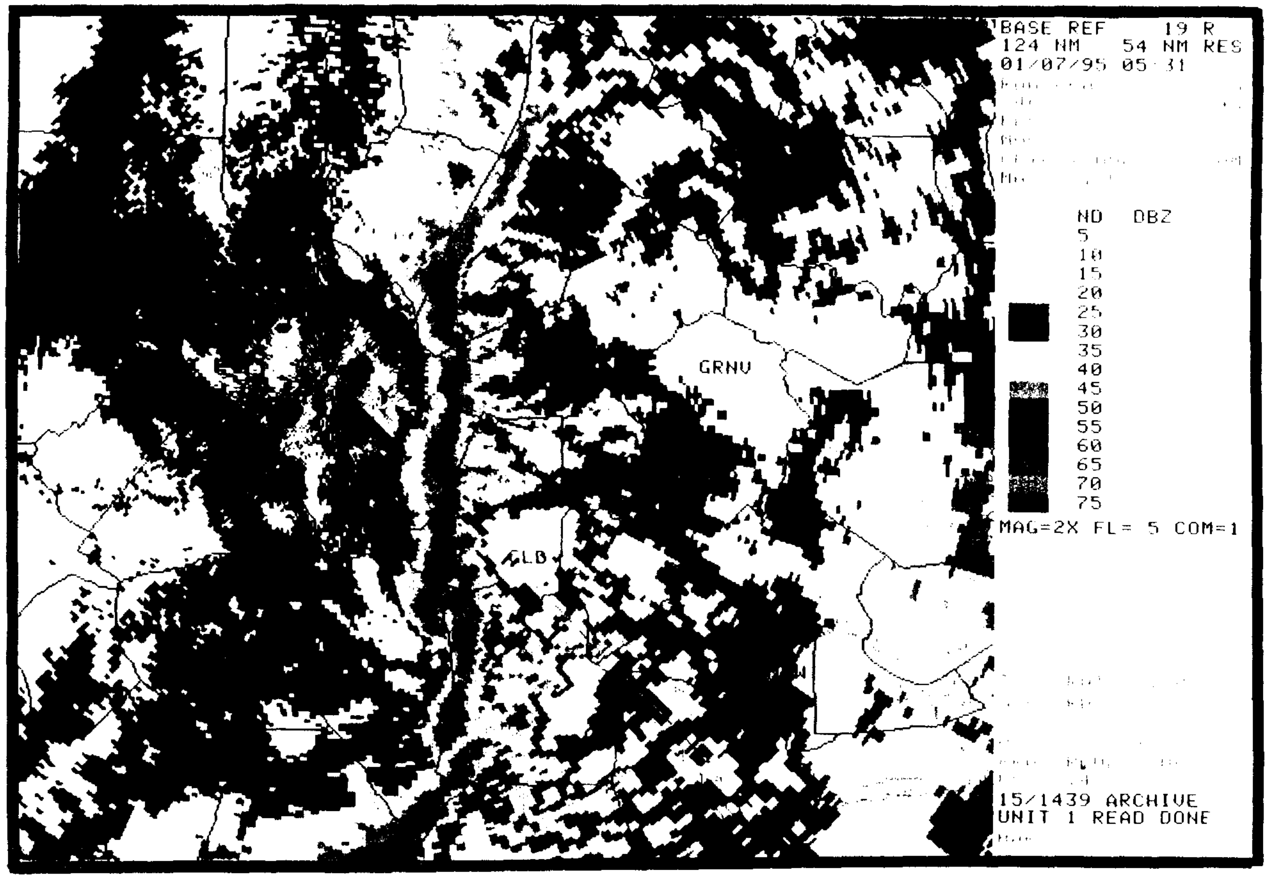


Figure 3.2.21a. Close-up WSR-88D reflectivity image of the squall line at 0531 UTC as it approached Goldsboro, North Carolina (GLD).

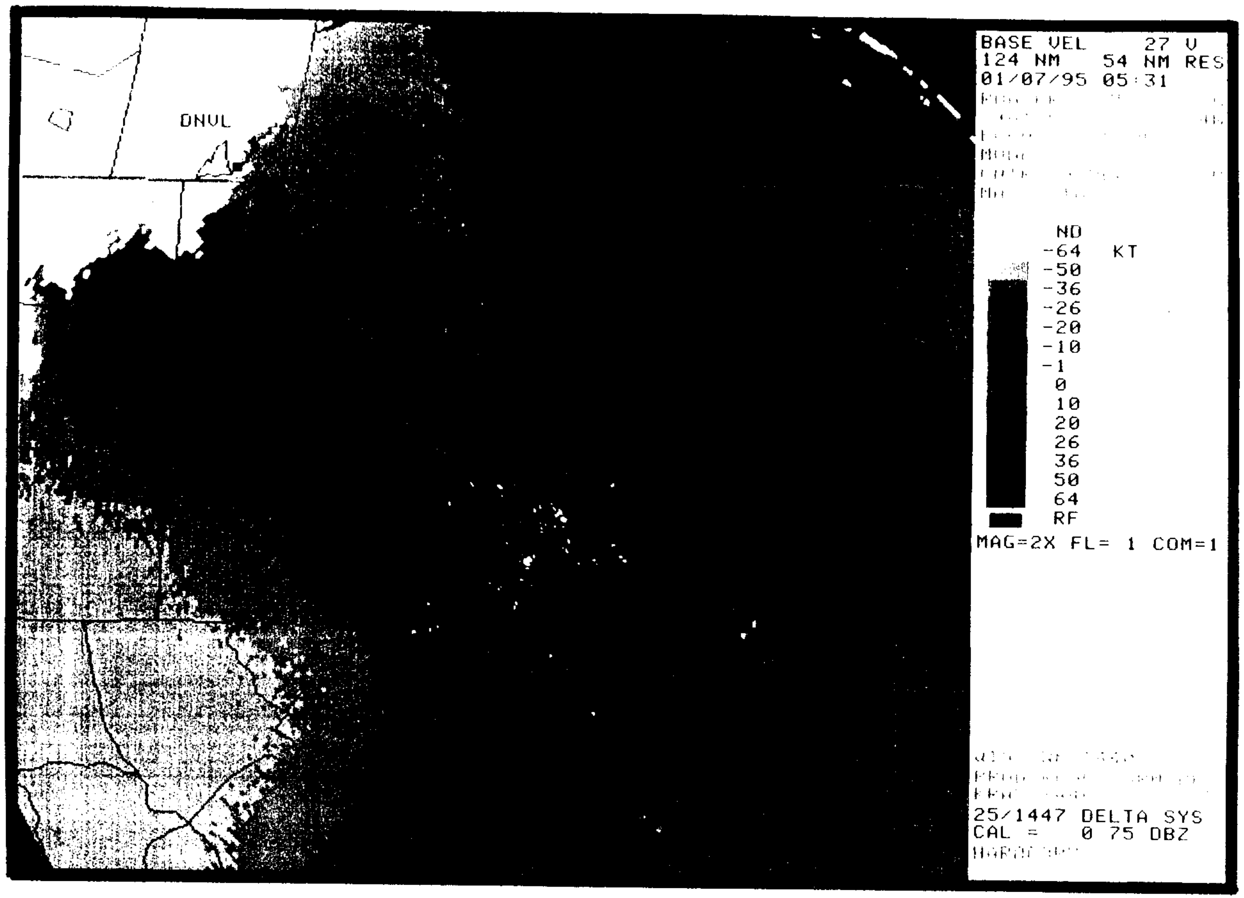


Figure 3.2.21b. Close-up WSR-88D velocity image of the squall line at 0531 UTC as it approached Goldsboro, North Carolina (GLD). Note the maximum velocities represented by arrows.

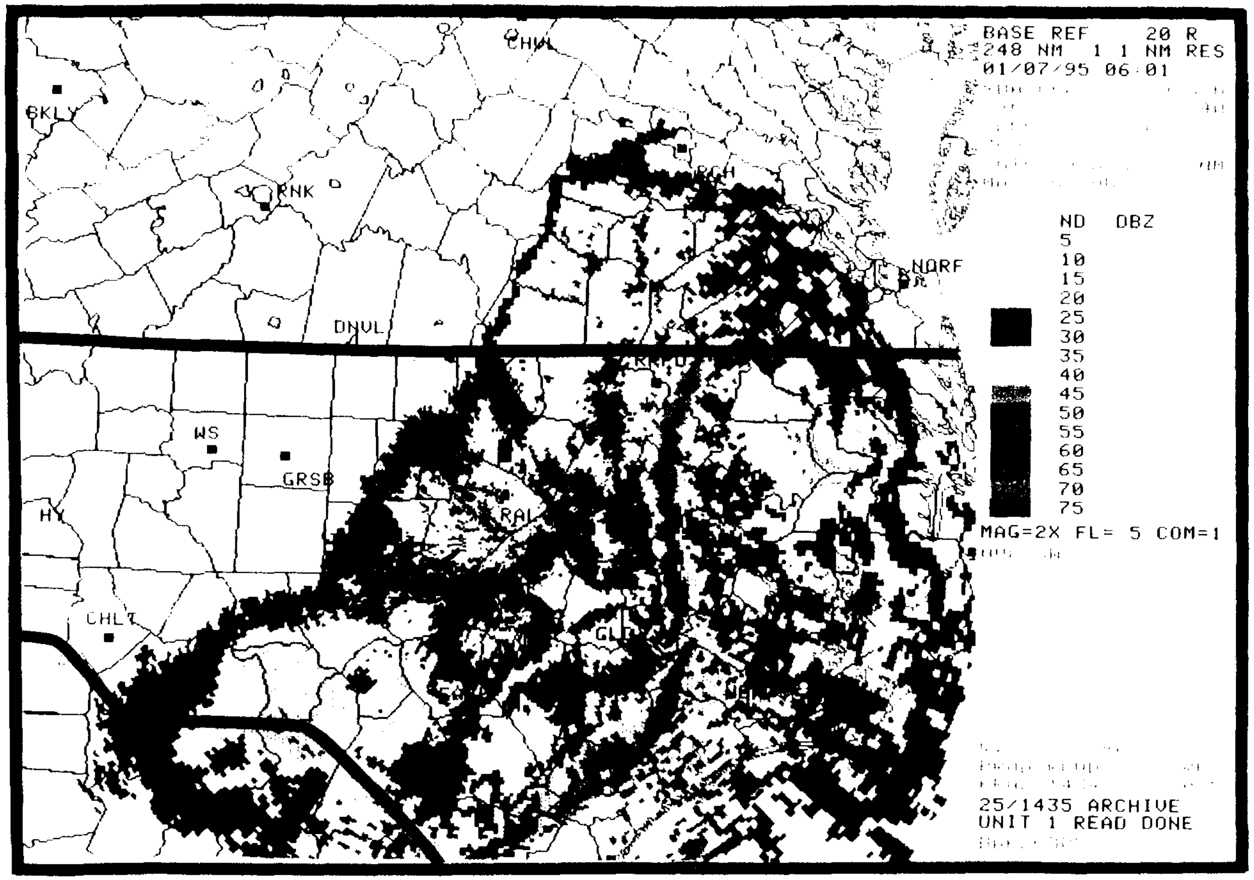


Figure 3.2.22. Same as Fig. 3.2.10 except for 0601 UTC 7 January 1995.

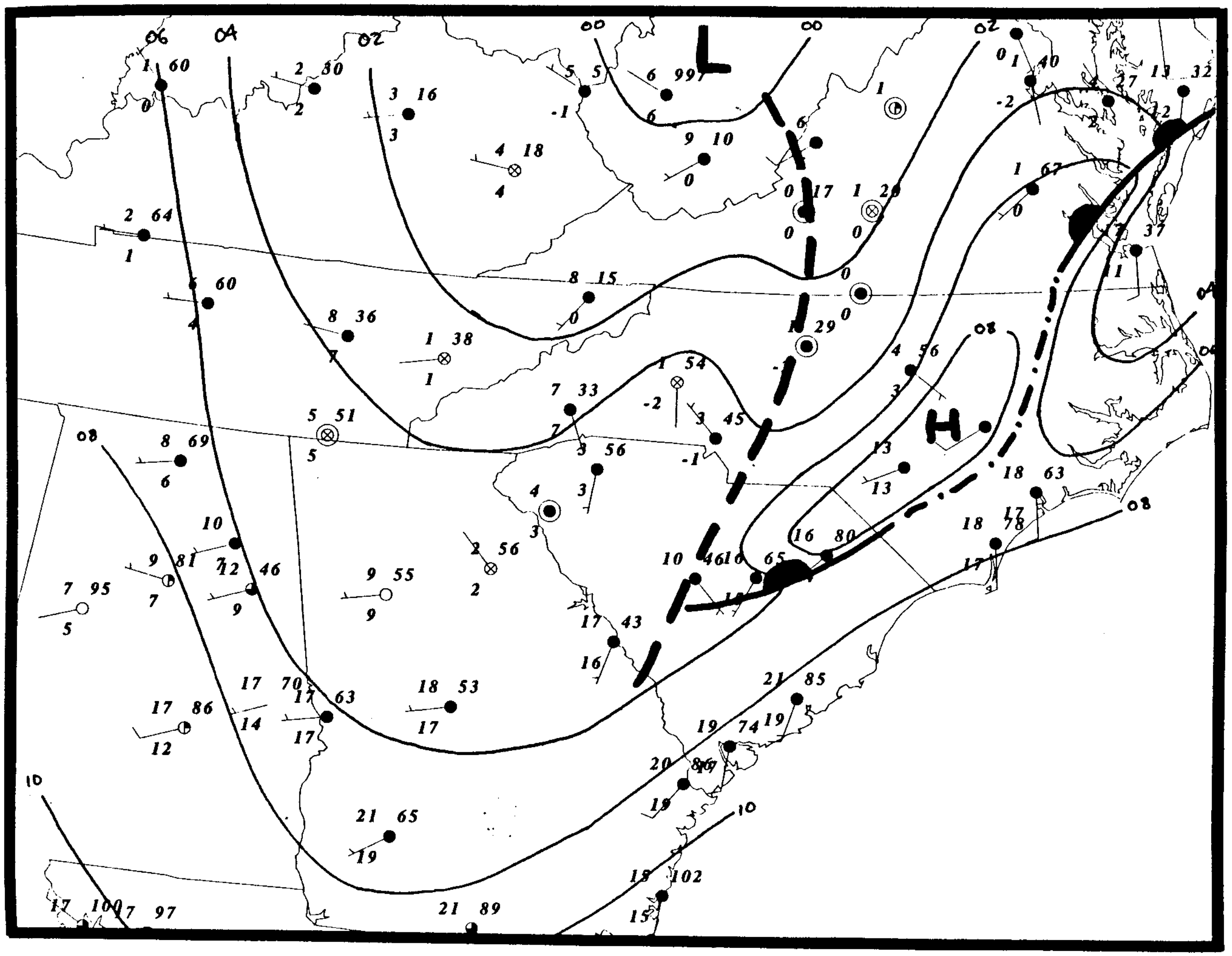


Figure 3.2.23. Same as Fig. 3.2.1 except for 0600 UTC 7 January 1995.

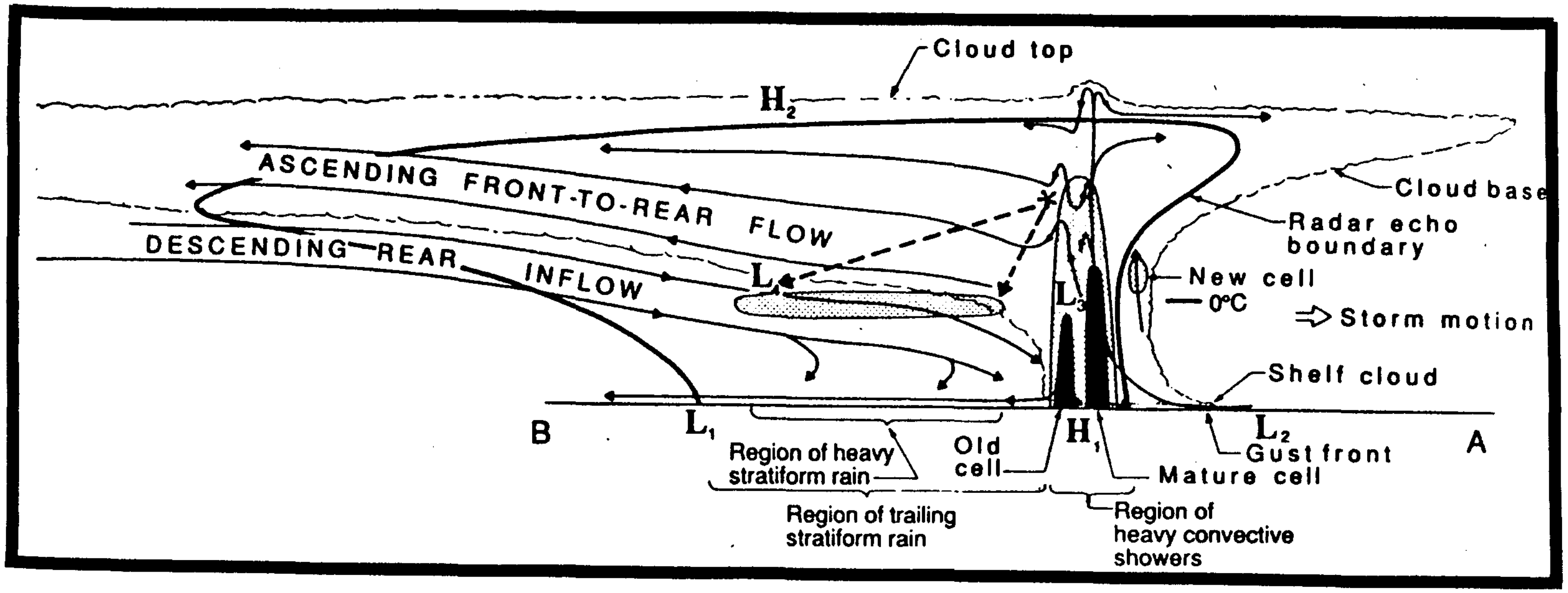


Figure 4.1. Schematic model of a squall line with trailing stratiform precipitation. Shaded area represent radar reflectivity core. Arrows represent air flow within storm (Houze, 1989).

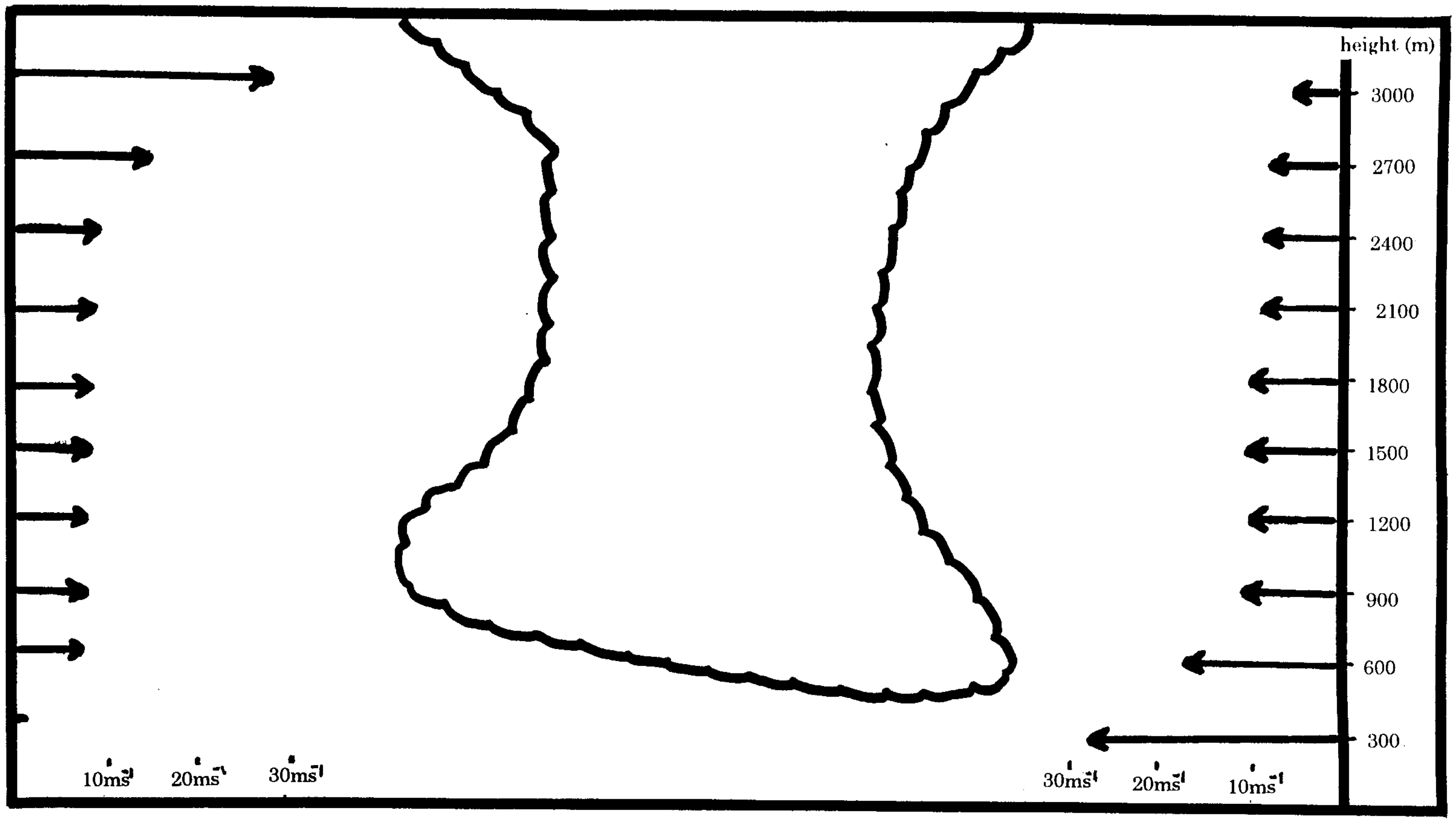


Figure 4.2. Plot of storm relative inflow ahead and behind the squall line. Components of wind normal to the storm are plotted in ms^{-1}.

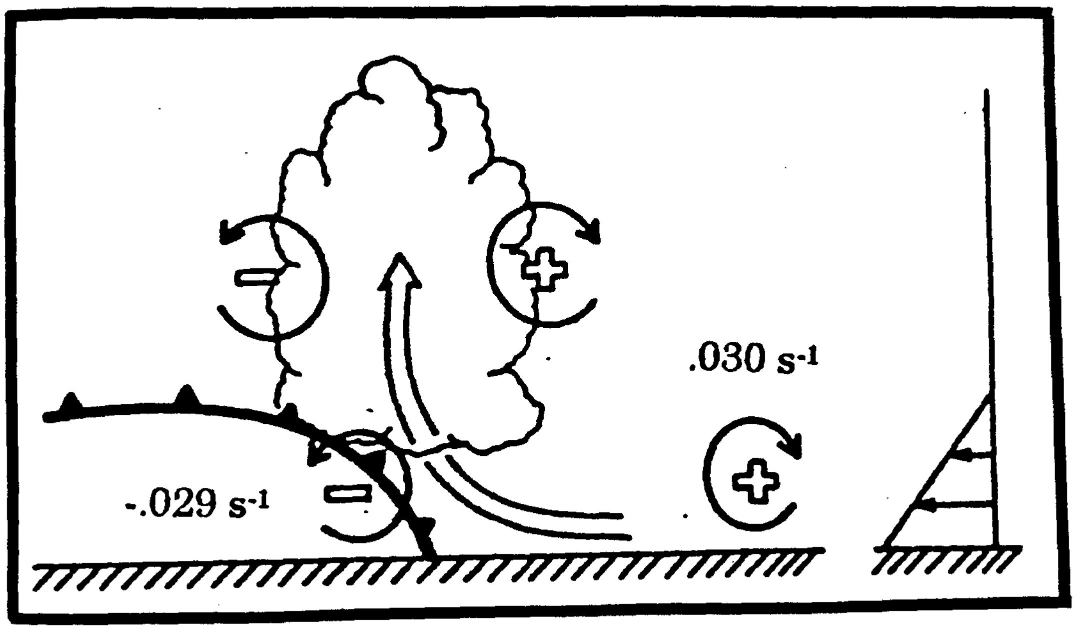


Figure 4.3. Schematic diagram showing buoyant updraft influenced by wind shear (arrows on the right) and a surface cold pool. (+) represents generation of positive vorticity. (-) represents generation of negative vorticity. Values depicted are calculated vorticity in s^{-1}. (After Rotuno et al., 1988).

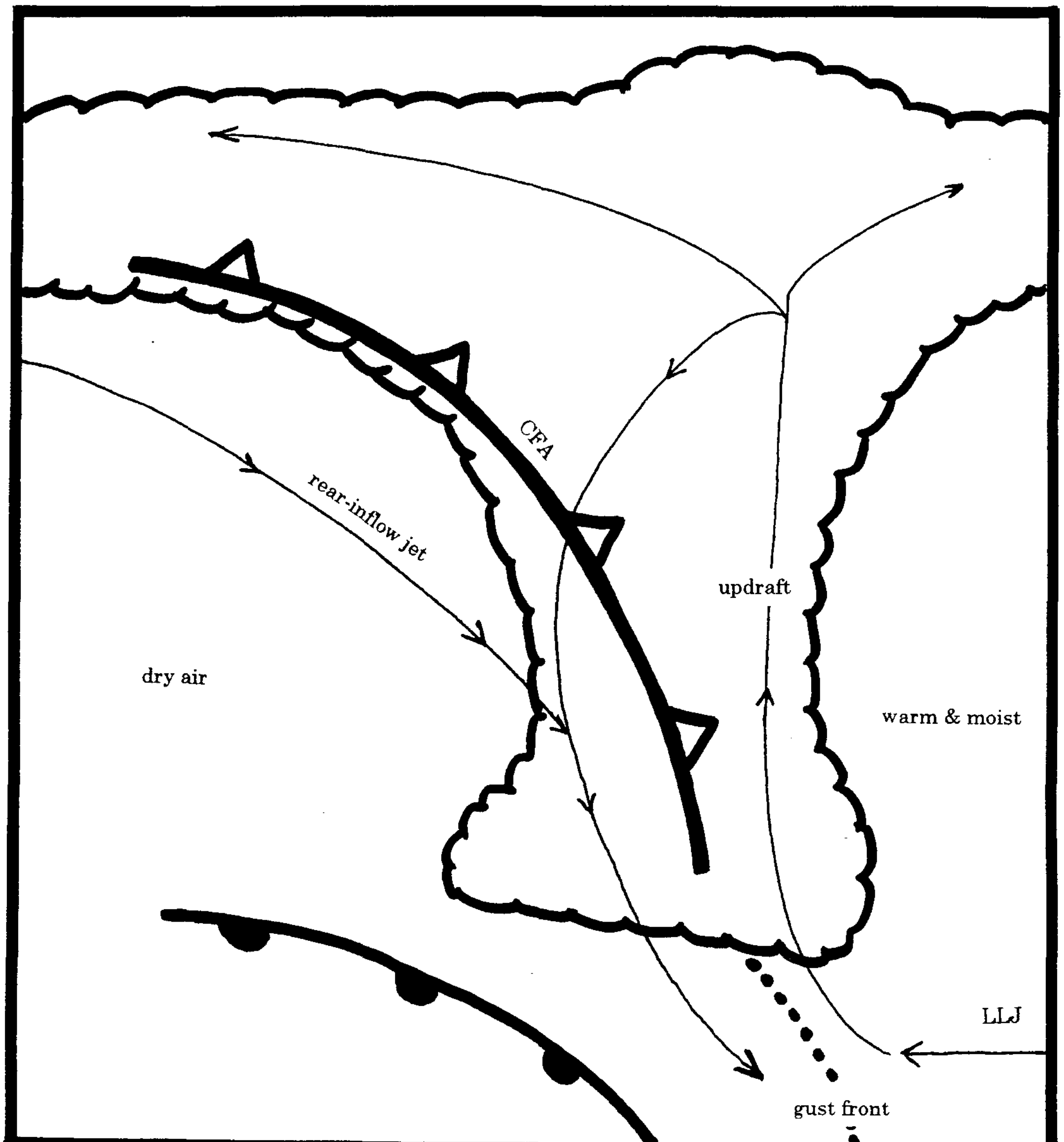


Figure 5.1. Schematic view of CFA and squall line evolution. LLJ is the low-level jet. CFA is the cold front aloft.